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## Summary

The motion of a deck influences both the difficulty of landing a helicopter on a vessel and the safety of a helicopter while it remains on the deck after landing. This report reviews the current practices applied to the landing of civil helicopters on the decks of vessels and makes recommendations for improved procedures.

The operators of civil helicopters currently specify deck motion limits for their aircraft in terms of roll and pitch displacements, which are measured by instruments on vessels. The rate of vertical motion (heave) is considered to be important by the operators, but it is only assessed visually by the pilot.

The motions of floating vessels are irregular, so short-term observations may not adequately predict the motions occurring at a later time. Measurement procedures should therefore take account of the statistical properties of the motions of vessels. There is a lack of consistency in the measurement and reporting of motions from different vessels. Procedures are recommended for standardising the measurement and reporting of vessel motions for comparison with deck motion limits.

The difficulty of the landing task is affected by the frequency of oscillation of the deck, as well as the roll and pitch displacement. The probability that a helicopter will slide on a deck after landing depends on the horizontal accelerations in the plane of the deck. The horizontal accelerations increase with the height of the deck and with the frequencies of the roll and pitch motions. It is recommended that procedures are developed for establishing an index of the severity of deck motions. This should be less dependent on the characteristics of individual vessels than is the measurement of angular displacements.

Helicopter low-airspeed performance envelopes are not adequately defined by manufacturers, making it difficult to establish crosswind operational limits by analytical means. It is recommended that certification standards should define the minimum information required in the flight manuals of helicopters which make landings on moving decks.

## Foreword

The research reported in this paper was instigated and funded by the Safety Regulation Group of the UK Civil Aviation Authority in collaboration with the UK Offshore Operators Association, the UK Government Health and Safety Executive and Department of Transport. The subject of this research project was first highlighted for attention in 1986 following an incident on a supply ship where a helicopter was nearly tipped over during passenger disembarkation/embarkation by excessive movement of the helideck. More recently, early in 1992 while this research was being conducted, an accident occurred during operations to a diving support vessel which resulted in a fatality.

The Authority accepts the findings of the research and action has already been taken to implement some of the recommendations made. Specifically: an amendment to CAA document CAP 437 has been issued revising Chapter 5, Section 3 to address the standardisation of procedures for reporting ship motion (Recommendation 9.1); discussions are taking place with aircraft manufacturers regarding the information content of flight manuals of helicopters which are used for operations to moving decks (Recommendation 9.5).

A further research programme has been instigated to address Recommendations 9.2, 9.3 and 9.4. The objectives of this work are to: (i) identify which parameters are required to quantify the severity of helideck motion, independently of vessel type and helideck location on the vessel, relative to helicopter landing and stability on the helideck; (ii) establish how they may be consolidated to form an index of helideck motion, and indicate how appropriate limits would be established for a given helicopter type in terms of the index; (iii) establish the relationship between the statistical confidence of the measurements of the characteristics of the helideck motion parameters, identified in (i), and the length of the period of observation; (iv) demonstrate the practicability of providing a low cost instrumentation package capable of automatically measuring the helideck motion parameters required by (i), calculating the helideck motion index and its relevant statistical characteristics, and displaying the information to be reported to the helicopter pilot.

# Contents

# 1 INTRODUCTION

The helicopter is an important component of the offshore oil industry, providing rapid and efficient transportation of personnel and equipment between fixed and mobile installations, ships and shore. However, the environment in which helicopters are required to operate can be hostile, presenting hazards such as high winds, high seas and reduced visibility. The operators have established the limitations of the helicopter in this environment largely by experience.

This report reviews current deck landing procedures and motion limits for both civil and military aircraft. The characteristics and motions of vessels to which helicopters are required to operate are examined. The information required from instrumentation on board vessels in order to determine whether the motion of a deck is acceptable, and likely to remain acceptable for the period that a helicopter is on the deck, is also considered. Improvements in the methods of observing and reporting ship motion measurements are recommended.

# 2 CHARACTERISTICS OF VESSELS WITH HELIDECKS

## 2.1 Motion characteristics

### 2.1.1 *Absolute motions of a vessel*

Ship motion occurs in three translational axes and three rotational axes (see Figure 1). Translational motions on the deck of a floating vessel have components which are proportional to the rotational motions and the distance from the centre of gravity. Hence the absolute translational accelerations (i.e. the accelerations in an inertial frame of reference) of a point p(X,Y, Z) on the deck are given by:

$$\ddot{s}_{px} = \ddot{s}_x + Z.\ddot{r}_y - Y.\ddot{r}_z$$

$$\ddot{s}_{py} = \ddot{s}_y + X.\ddot{r}_z - Z.\ddot{r}_x$$

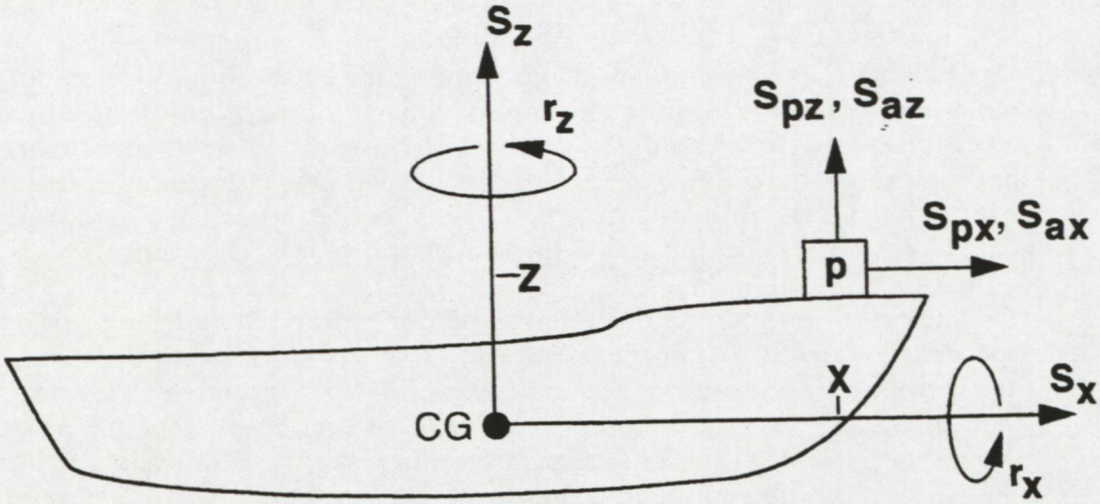
$$\ddot{s}_{pz} = \ddot{s}_z + Y.\ddot{r}_x + X.\ddot{r}_y$$

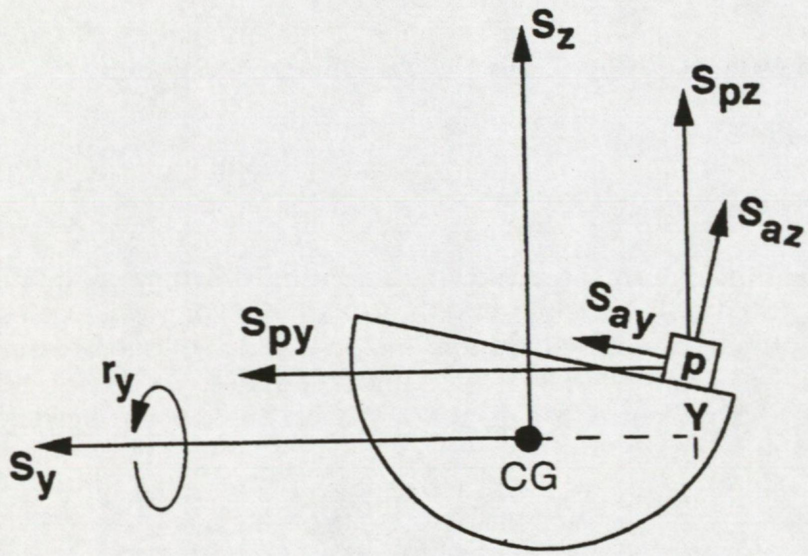
where X, Y and Z are the distances of point p from the centre of gravity of the vessel in each axis, $\ddot{s}_x$, $\ddot{s}_y$ and $\ddot{s}_z$ are the translational accelerations at the centre of gravity and $\ddot{r}_x$, $\ddot{r}_y$ and $\ddot{r}_z$ are the rotational accelerations in roll and pitch and yaw (see Figure 1). The velocities and displacements of point p(X,Y,Z) may be found by integrating the above equations with respect to time.

### 2.1.2 *Accelerations and forces in the plane of a deck*

An object on a moving deck is subject to the components of gravity resolved in directions normal and parallel to the deck. The apparent accelerations, $\ddot{s}_{ax}$, $\ddot{s}_{ay}$ and $\ddot{s}_{az}$, experienced by the object in the plane of the deck (see Figure 1) are given by:

$$\ddot{s}_{ax} = \ddot{s}_{px} + g.\sin(r_y) \approx \ddot{s}_{px} + g.r_y$$




| | | |
|---|---|---|
| $s_x$, $s_y$, $s_z$ | = | translational displacements of the CG |
| $r_x$, $r_y$, $r_z$ | = | angular displacements of the CG in roll, pitch and yaw |
| $s_{px}$, $s_{py}$, $s_{pz}$ | = | translational displacements of an object on the deck at p(X,Y,Z) |
| $s_{ax}$, $s_{ay}$, $s_{az}$ | = | translational displacements of an object at p(X,Y,Z) in the plane of the deck |

**Figure 1 Axes of measurement of vessel motions**

$$\ddot{s}_{ay} = \ddot{s}_{py} + g.\sin(r_x) \approx \ddot{s}_{py} + g.r_x$$

$$\ddot{s}_{az} \approx \ddot{s}_{pz} + g$$

where g is the gravitational constant. Hence, for small angles and where the lateral and longitudinal accelerations are small, $\ddot{s}_{ax}$ and $\ddot{s}_{ay}$ are approximately proportional to the pitch and roll inclinations.

The longitudinal, lateral and vertical forces acting on an object, of mass m, in the plane of the deck are:

$$F_{Long} = m.\ddot{s}_{ax}$$

$$F_{Lat} = m.\ddot{s}_{ay}$$

$$F_{Vert} = m.\ddot{s}_{az}$$

If the longitudinal acceleration and other forces acting on the object are small, an object will slide on a smooth deck when:

$$|F_{Lat}| > \mu.F_{Vert}$$

where $\mu$ is the coefficient of friction between the object and the deck. The object will topple when:

$$|F_{Lat}| > \frac{l}{2h} F_{Vert}$$

where $l$ is the length of the contact area of the object with the deck in the lateral axis, and $h$ is the height of the centre of gravity of the object above the deck. Similar relationships exist for logitudinal forces.

The apparent lateral acceleration in the plane of the deck, $\ddot{s}_{ay}$, has been referred to as the Lateral Force Estimator (LFE) (Baitis *et al*, 1984; Lloyd, 1989; Graham, 1990; Graham *et al*, 1991). The LFE is the force per unit mass acting in the lateral direction on an object or a person on the deck. Graham (1990) has suggested that the LFE can be related to the incidence of 'motion induced interruptions', which cause personnel working on a moving deck to lose their balance. Graham *et al* (1991) have proposed a generalised lateral force estimator, which is a function of forces due to roll, pitch, longitudinal, lateral and vertical accelerations. The incidence and severity of objects sliding on a deck in a given sea condition may be predicted from the spectral moments of the generalised lateral force estimator.

### 2.1.3 *Motions of ships*

Figure 2 shows the power spectral densities of the accelerations, measured in the three translational axes of a 4000 ton ship, as a function of frequency and measurement position (Lawther, 1982). The lateral (y-axis) acceleration is dominated by the roll response of the ship. The roll response is characterised by a pronounced resonance with a period of approximately 10 s (0.1 Hz). At very low frequencies, the roll inclination of the vessel follows the wave slopes, but at the resonance frequency the roll amplitude may be more than five times greater than the prevailing wave slopes. The damping of the roll response tends to increase with increasing forward speed, resulting in some reduction in both roll amplitude and frequency (Lloyd, 1989). It can be seen from Figure 2 that the lateral acceleration increases toward the stern of the ship and with height above the keel.

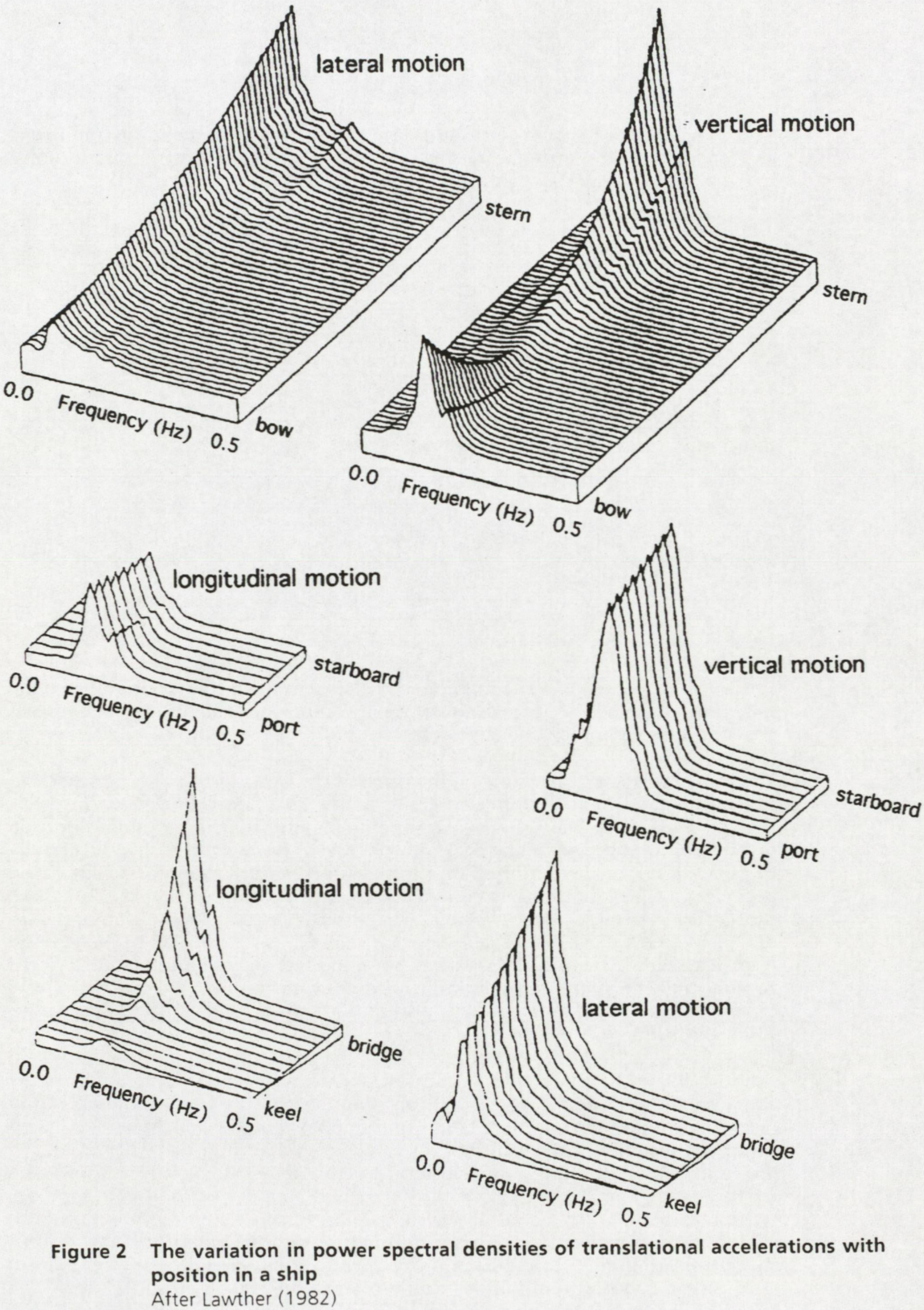



**Figure 2 The variation in power spectral densities of translational accelerations with position in a ship**
After Lawther (1982)

Generally, the roll periods of geometrically similar ships vary with the square root of the linear dimension. Hence, the rolling period of a ship with a length of 200 m can be expected to be of the order of $\sqrt{2}$ greater than that of a geometrically similar 100 m ship (Rawson and Tupper, 1976). The roll period may also be affected by loading conditions (see Section 2.1.4).

The vertical (z-axis) and logitudinal (x-axis) accelerations are dominated by the pitch response of the ship. The pitch response of a conventional ship is more damped than the roll response, and so the pitch motion tends to reflect the wave encounter spectrum. In this case the pitch acceleration peaks at about 0.2 Hz (a period of 5 s). The vertical acceleration tends to be a minimum near to amidships, and increases towards the bow and the stern. There is little difference between the vertical motions on the port and starboard sides of the ship.

The motions of a ship in any axis depend on the encountered wave elevations and slopes as well as the characteristics of the vessel. For a moving ship, the wave encounter spectrum is dependent on the ship's speed and heading. Figure 3 shows the variations in the motions of a 4000 ton fisheries protection vessel at different headings, in the same sea conditions (Lewis *et al*, 1986). The motions tend to be greater in a following or beam sea than with a head sea. The magnitude of the roll motion is significantly reduced by the vessel's fin stabilisers, but the stabilisers can also alter the frequency of the roll motion.

### 2.1.4 *Motions of semi-submersibles*

The acceleration power spectral densities shown in Figure 4 were computed from the translational accelerations at the drill floor of a semi-submersible platform by Lewis and Griffin (1990). Semi-submersible platforms have much longer roll periods than ships, of the order of 40 s. The pitch response of a semi-submersible is less damped than that of a conventional ship, and is characterised by a resonance at a similar frequency to that in roll. The acceleration spectra for the lateral and longitudinal axes can be seen to have peaks both at the resonance frequency and at wave encounter frequencies.

The motions of the semi-submersible shown in Figure 4 can be seen to be affected by the draught, which is dictated by loading and ballast conditions. At smaller draughts, the vessel has a smaller metacentric height (GM). The GM is the length of the righting lever, which opposes the inclining forces of the waves and wind. For small angles, the resonance frequency, $f_n$, of the vessel's response is approximated by:

$$f_n = \frac{\sqrt{g.GM}}{2\pi.k}$$

where k is the radius of gyration of the mass about the centre of rotation and g is the acceleration due to gravity. Under similar sea conditions, the root-mean-square accelerations measured in the x- and z-axes at the centre of the drill floor were twice as large with a longitudinal GM of 2.78 m (which corresponded to a draught of 18.3 m) as they were with a GM of 3.32 m (corresponding to a draught of 21.3 m).

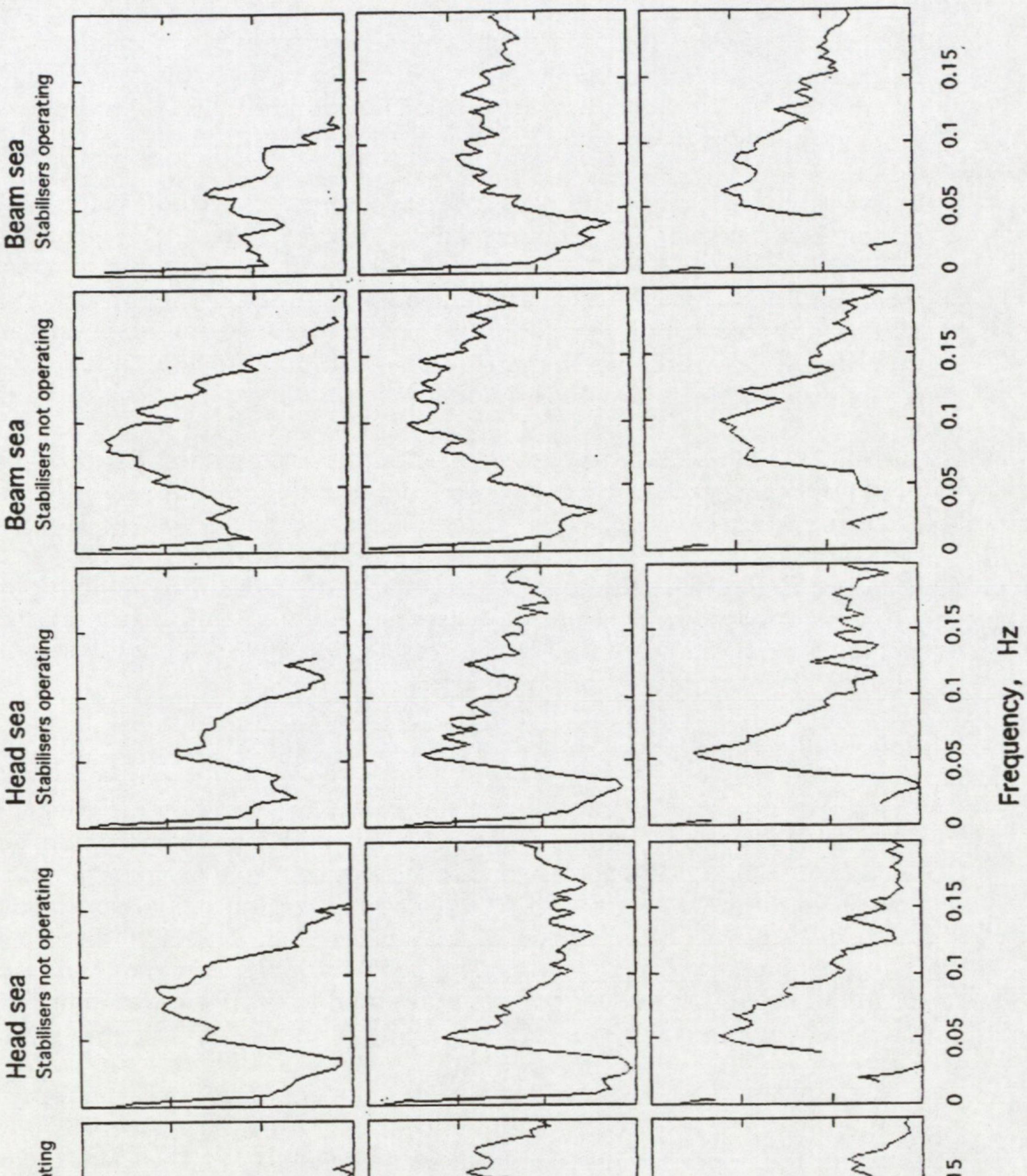



**Figure 3 Power spectral densities of roll and pitch and heave displacement of a ship at different headings, in the same sea conditions, with and without fin stabilisers operating**

After Lewis *et al* (1986)

Resolution = 0.02 Hz, degrees of freedom = 32

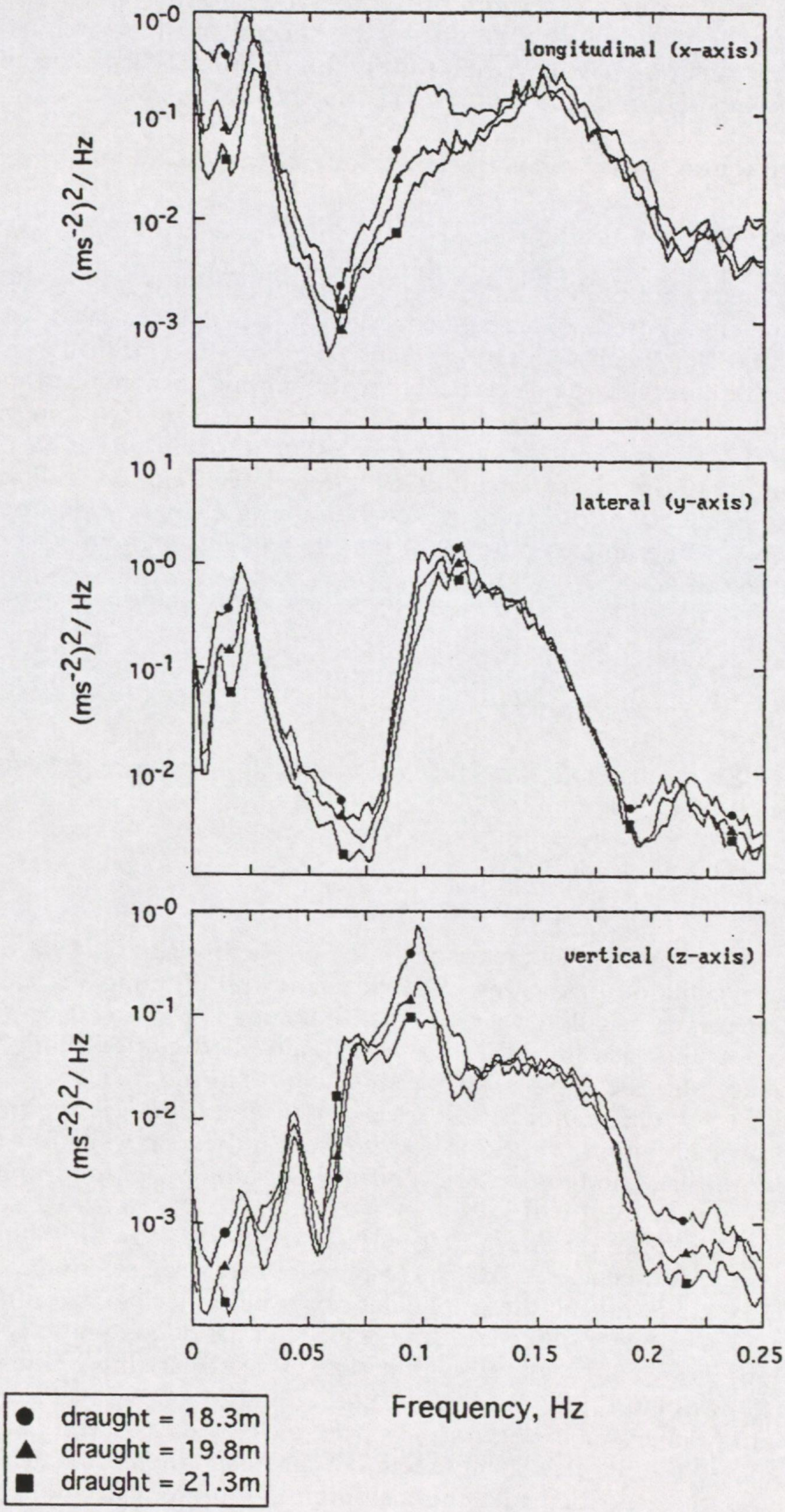



**Figure 4 A comparison of power spectral densities of accelerations in the three translational axes of a semi-submersible drilling rig at three draughts**

After Lewis and Griffin (1990)

Resolution = 0.002 Hz, degrees of freedom = 88

At low frequencies, the spectra of the roll and pitch displacements of the semi-submersible platform were similar to the spectra of the lateral and longitudinal accelerations (see Figure 5). However, the rotational displacements decreased rapidly with frequency above 0.1 Hz (a period of 10 s).

## 2.2 Instrumentation for measuring motions of vessels

### 2.2.1 *Inclinometers*

Inclinometers are used to indicate the inclinations of a vessel in roll and pitch. An inclinometer consists of an element, such as a pendulous mass, which is free to move and align itself with the gravitational vector. The inclination is measured by sensing or observing the displacement of the moving element relative to the body of the instrument, which moves with the ship. The accuracy of an inclinometer is affected by lateral motion at the pivot (in the plane of the instrument). The magnitude of the measurement error due to lateral motion is dependent on the natural frequency of oscillation, $f_n$, of the moving element about the pivot. Lateral motions at frequencies much less than $f_n$ will result in an offset $\delta\theta$ (radians) equivalent to:

$$\delta\theta = \ddot{d}_y/g$$

where $d_y$ is the lateral displacement of the pivot. At frequencies much greater than $f_n$, the offset is equivalent to:

$$\delta\theta = d_y.\frac{(2\pi.f_n)^2}{g}$$

Most vessels have inclinometers mounted on the bridge, to give a visual indication of the inclination of the vessel in pitch and roll. The moving element in these instruments is usually either a short, undamped, pendulum or a bubble of gas moving against a calibrated scale in a liquid-filled curved tube. The resonance frequency of these devices is typically higher than the frequencies of the motion, and so they will respond to horizontal acceleration. Hence the vertical and longitudinal location of the inclinometer within the ship will affect the accuracy of the roll readings, and the vertical and lateral location will affect the pitch readings.

In a sea trial on a U.S. Navy destroyer, Baitis (1975) found that there was a poor correlation between pitch and roll amplitudes measured electronically, using a gyro stabilised platform, and the amplitudes observed on inclinometers mounted on the bridge. Inclinometer observations were made of the double amplitude pitch and roll motions associated with helicopter take-offs and landings, and compared with recordings of roll and pitch time histories. The timing of the readings was a potentially large source of errors, since the inclinometer observer on the bridge was not able to see the helicopter landing deck. Hence the inclinometer readings may not have corresponded with the measurements made from the recordings, which were electronically timed with the take-off or landing event. However, most of the inclinometer observations were larger than the electronic measurements, sometimes by a factor greater than two.

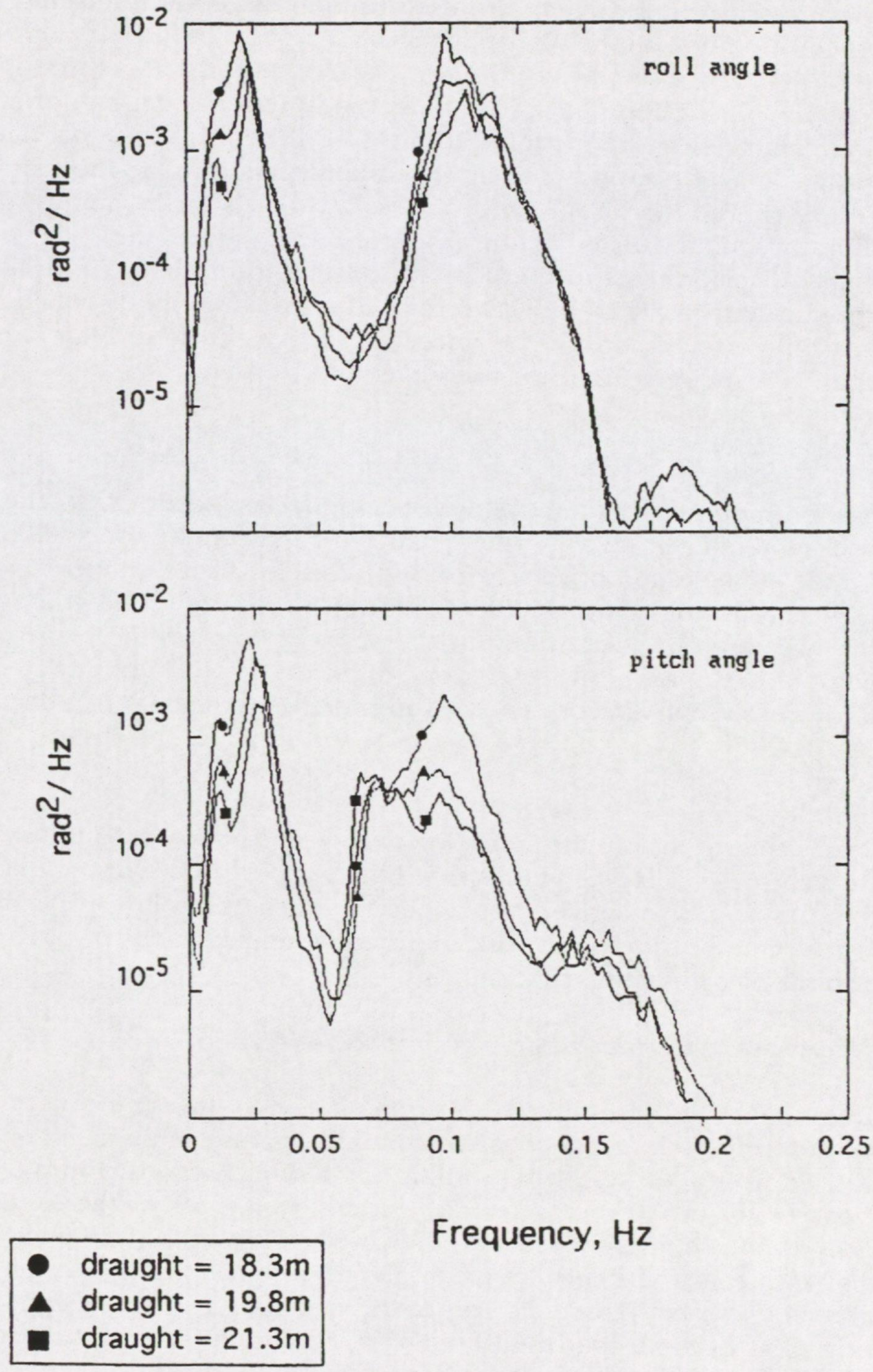



**Figure 5 A comparison of power spectral densities of roll and pitch displacements of a semi-submersible drilling rig at three draughts**

After Lewis and Griffin (1990)

Resolution = 0.002 Hz, degrees of freedom = 88

### 2.2.2 *Vertical reference systems*

Vertical reference systems are used to provide data to 'dynamic positioning systems'. Dynamic positioning systems are used to drive thrusters to maintain a vessel at a particular location on the surface of the sea.

Typical vertical reference systems incorporate an inertial platform, upon which accelerometers can be mounted to measure the translational accelerations in the inertial frame of reference. Ideally, they are mounted close to the centre of gravity of the vessel. The inertial platform acts as a two-axis inclinometer with a very low natural frequency of oscillation (the period may be of the order of 100 s). The angular displacements of the platform relative to the body of the instrument are sensed electronically by inductive coils. The resulting signals may be displayed on electronic displays, or may be stored and processed to give an indication of the variation in the vessel motions over time.

### 2.2.3 *Accelerometers*

Accelerometers provide an electronic signal proportional to the translational acceleration in a given axis. The signals can be integrated, after suitable filtering, to provide an indication of velocity or displacement. Accelerometers may be mounted on an inertial, or gyro-stabilised, platform to measure accelerations in the inertial frame of reference. Alternatively, they may be fixed in the plane of the deck to measure the apparent accelerations of an object, including the components of gravity resolved in directions normal and parallel to the deck (see Section 2.1.2).

### 2.2.4 *Gyros*

Gyros can give an accurate indication of angular motions when translational motions are also present. Larger vessels may be equipped with gyro-stabilised navigational compasses, or gyro driven roll stabilisers. Pitch and roll displays driven by these instruments provide crews with more accurate indications of pitch and roll angle than are possible with inclinometers.

### 2.2.5 *Differences in instrumentation between vessels*

There is a large variation in the instrumentation for measuring motions on different vessels. One of the more sophisticated installations can be found on the BP Seillan 'Oil Pumping Vessel'. The Seillan has a dynamic positioning system which incorporates two 'vertical reference systems' with gyros and accelerometers, a wave rider buoy and an infra red wave height recorder. Roll, pitch and heave (vertical) displacements of the helideck are displayed on visual display units on the bridge and in the radio room. These displays give instantaneous values of each of the motions as well as maxima over the previous 1, 10 and 20 minutes and trends over the previous 4 or 5 days.

The diving support and multi support vessels (D.S.V. and M.S.V.) operated by Stena Offshore Ltd. have vertical reference systems, mounted near the bridge. These do not measure heave motion, which is usually estimated by experience from the sea state. The display of information from these systems varies from direct readouts, on the older vessels, to computerised display systems which can store and plot time histories over preceding time intervals.

The fleet of semi-submersible flotels operated by SAFE Service currently employ only visual inclinometer instruments, which are located in the pilot house. Heave is estimated from the wave height, usually by reference to a nearby fixed structure. The pilot house is located at approximately the same vertical level as the helideck.

Semi-submersible drilling rigs are equipped with instrumentation to measure heave at the centre of the drill floor, but this is some distance from the helideck. The motions at the drill floor may be measured from the displacement of the riser tensioner, or via vertical reference systems.

## 2.3 Motion prediction

It is possible to make short term predictions of the motions of a ship using adaptive Kalman filtering techniques (Sidar and Doolin, 1983; Triantafyllou *et al*, 1983; Broome and Pittaras, 1990). These techniques are used in dynamic positioning systems (see Section 2.2) to determine the thruster response necessary to counter the tendency of waves to drive the vessel off station. However, accurate predictions are only possible for up to 15 seconds, which is little more than the period of a single roll of a typical ship. Longer term predictions of ship responses can only be made on a statistical basis (Ochi and Bolton, 1973).

Wave elevations and slopes, and their consequent ship responses, are narrow-band random processes. If the ship responses, h(t), are sampled at fixed time intervals, the samples will follow a Gaussian probability function (Lloyd, 1989). Gaussian probability distributions are uniquely defined by their standard deviation, $\sigma$. The estimation of the standard deviation of the ship responses requires an instrument which is capable of sampling the responses over a long period, but such instruments are not generally available on ships.

More traditional methods of measuring wave amplitudes and ship motions are based on observing successive ship response amplitudes, $h_a$ (see Figure 6). The short term variations in the amplitudes have been shown to follow a Rayleigh distribution (Lloyd, 1989). The traditional average response is the significant amplitude, $\bar{h}_{1/3}$, which is defined as the mean value of the highest third of all the response amplitudes. The significant amplitude is equal to $2\sigma$, where $\sigma$ is the standard deviation of the response time history, h(t).

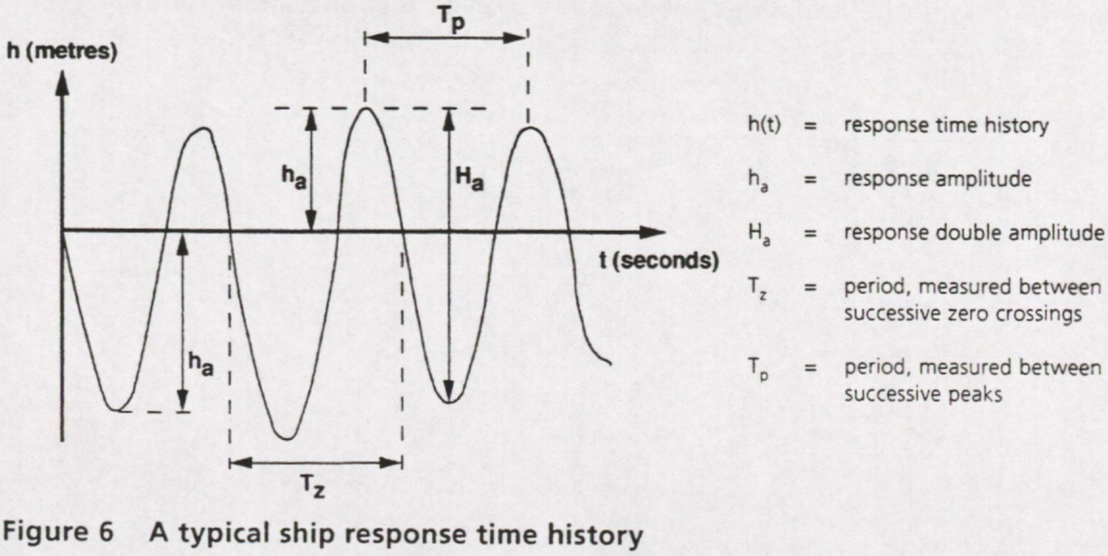



**Figure 6 A typical ship response time history**

The significant wave height is closely related to an experienced observer's estimates of the average wave height (Baitis, 1975; Lloyd, 1989). The experienced sailor's estimates of 'average' ship motions may also be similar to their significant amplitudes. Renirie and Hoekstra (1979) have suggested that although a good indication of the significant amplitude may be obtained many times by direct observation, the estimates can be inconsistent in some situations or when given by different persons. They proposed that a simple estimate of whether or not a rolling or pitching motion will exceed a certain limit may be obtained by counting the number of times that the amplitude exceeds the corresponding 2σ value, calculated from the Rayleigh distribution.

Table 1 shows the probabilities of exceeding certain values of $h_a/\sigma$ according to the Rayleigh distribution. It can be seen that an amplitude of 2σ can be expected to be exceeded by 13.5% of the observations, whereas an amplitude of 3.72σ will only be exceeded by 0.1% of the response amplitudes. Thus for a 0.1% probability that the roll amplitude will exceed 3 degrees in either direction:

$$2\sigma = \frac{6}{3.72} = 1.61\ \textit{degrees}$$

Therefore, if the roll amplitude exceeds 1.61 degrees in less than 13.5% of a long enough series of observations, the probability of exceeding a 3 degrees roll limit is less than 0.1%. Counting methods have the disadvantage that the observer needs to know the motion limit before the observations are made (see Section 5.2.1).

The accuracy of the above procedures depends on the number of observations. The standard deviation of the underlying probability distribution is representative of an infinitely long time history of ship motion, over which the ship and sea conditions are constant. Baitis (1979) suggests that for Naval ships, sample lengths of 18 to 30 minutes, or 200 cycles of ship motion, are generally sufficient to describe the true standard deviation of the infinite response time history. Renirie and Hoekstra showed that, on one ship in the North Sea, there was a large variation in the number of times that the measured 2σ amplitudes were exceeded during 256 second test runs. Over 44 test runs the roll amplitude exceeded 2σ between 4 and 18 times, with a mean of approximately 9. The pitch amplitude also exceeded 2σ between 4 and 18 times, with a mean of approximately 11.

**Table 1 Probability of exceeding given response amplitudes**

| $h_a/\sigma$ | *Probability of exceedance* |
|---|---|
| 0.00 | 1.0000 |
| 1.00 | 0.6060 |
| 2.00 | 0.1350 |
| 2.50 | 0.0440 |
| 3.00 | 0.0110 |
| 3.50 | 0.0020 |
| 3.72 | 0.0010 |
| 4.00 | 0.0003 |
| 4.29 | 0.0001 |

On a typical ship, with a roll period of the order of 10 s, there will be approximately 51 roll responses during a 256 s period. Confidence intervals can be established for the variance of a normally distributed variable using the $\chi^2$ distribution. The 99% confidence intervals for the estimated variance of the infinite response time history are given by:

$$\frac{nS^2}{\chi^2_{.995}} < \sigma^2 < \frac{nS^2}{\chi^2_{.005}}$$

where $S^2$ is the variance of a sample response time history consisting of n responses. If 50 observations are made there will be a 99% probability that $\sigma$ lies between 0.79 S and 1.33 S. However, if 100 observations are made there will be a 99% probability that $\sigma$ lies between 0.84 S and 1.22 S.

The availability of an instrument capable of directly sampling the motion time histories at fixed intervals would make it possible to compute the standard deviation associated with the Gaussian probability distribution and establish confidence intervals for probabilities of exceedance, taking into account the length of the record.

## 2.4 Landing deck characteristics

### 2.4.1 *Certification standards*

The certification standards for offshore helidecks are defined in CAP 437 (Civil Aviation Authority, 1983). These standards apply to deck location, size, obstacle free areas, marking and lighting.

### 2.4.2 *Location of the deck*

Mobile rigs are equipped with large helidecks, located in one corner of the structure, generally above the accommodation block. The location of helidecks on ships varies between vessels. The most common location is high on the bow of the ship, above the forward superstructure. Some ships have helidecks mounted lower on the bow, in front of the bridge superstructure. Other ships have decks mounted amidships, in which case the only clear access may be from the side. Stern mounted decks are generally clear of large obstructions. Some examples of deck layouts are shown in Appendix A.

### 2.4.3 *Wind over the deck*

Turbulence around the deck can have a significant effect on helicopter power margins (Johnston, 1971; see Section 3.1). Factors affecting turbulent airflow around a landing deck can be determined by wind-tunnel tests (Healey, 1991) and by analytical modelling (Healey, 1987). Mobile rigs may have turbulence hazards due to clad derricks and turbine exhausts, in addition to 'cliff edge' effects due to their location on top of the accommodation block. Von Blohm *et al* (1979) have shown that turbulence around oil-rig helidecks can be significantly reduced by providing a lip or air gap between the deck and its supporting structure.

Naval vessels generally have helidecks mounted low on the stern of the ship, behind the hangar superstructure and engine exhausts. The superstructure provides visual cues of deck motion, but can result in turbulence hazards for forward facing or relative wind landings (see Section 6.1.2). High mounted helidecks on oil industry support vessels generally present few turbulence hazards to a helicopter.

### 2.4.4 *The size of the deck*

The size of the deck has a great impact on the difficulty of the landing task, since it determines the clearance between the helicopter and any surrounding structures. Johnston (1971) has shown that, during deck landing trials at sea, the probability of landing further away from the optimum deck spot increases as deck movement becomes greater. A greater increase in position errors was observed in the lateral axis of the helicopter, compared to the longitudinal axis.

### 2.4.5 *The deck surface*

Helicopters may slide on a deck when the friction between the tyres and the deck surface is insufficient to counter forces due to rotational displacements, horizontal accelerations and wind. Wei *et al* (1991) have shown that with no wind, an SH-2F helicopter which is lined up with the principal axis of a naval destroyer will not slide on a new, dry deck until the roll inclination exceeds 26 degrees. However, the sliding threshold is reduced to 19 degrees if the deck surface is worn, 12 degrees if the deck is wet and 6 degrees if it is oily.

The friction of civil helidecks is normally augmented by a rope net. The certification standard for offshore helicopter landing areas, CAP 437 (Civil Aviation Authority, 1983), requires that 'a tautly stretched rope netting should be provided to assist in the stability of helicopters on the deck, particularly those with wheeled undercarriages in adverse weather conditions'. The standard recommends a rope diameter of 20 mm, with a maximum mesh size of 200 mm. The rope should be secured every 1.5 m and tensioned to at least 2225 N. The effect of a deck net has not been modelled. Several incidents have been reported since deck nets became mandatory where aircraft have moved on the deck by up to 4 feet (see Section 4).

Helicopter crews may request the helicopter landing officer to insert wheel chocks while the helicopter is standing on the deck of a vessel. The helicopter operators do not have any mandatory requirement for chocking wheels when standing on decks. Some pilots believe wheel chocks to be beneficial and others do not, but no quantitative data have been found to support these views.

### 2.4.6 *Visual cues*

The final phase of a deck landing, including transition to hovering flight and translation to the point where the vertical landing is commenced, is accomplished primarily by visual reference to the point of intended landing. In interviews with U.S. Navy fleet pilots, Mitchell and Douglas (1979) determined that good sources of visual information are needed for wind direction, ship motions, obstacle clearance, a horizontal reference, tracking errors and rates, hover height and closure rates. A view of the ship structure was considered to be a strong source of visual information. The hangar and forward structure of naval ships were believed to provide important depth perception to the pilot. These visual cues are not available when making forward facing landings on bow mounted decks. The line-up markings on a helideck were reported to provide a good visual reference while approaching a ship, but may not be visible when hovering over the landing area.

## 3 HELICOPTER CHARACTERISTICS

### 3.1 Aerodynamic characteristics

A helicopter performance envelope, showing the power required as a function of airspeed and direction, is shown in Figure 7 (Kolwey, 1977). A large amount of induced power is required to maintain the aircraft in a stationary hover. This falls off rapidly with increasing airspeed in any direction, due to the increased mass of air which is encountered by the rotor (Fradenburgh, 1990). The performance margin (the difference between available power and required power) can therefore be significantly enhanced by wind over the deck.

The required power increases after the forward airspeed exceeds a certain value, due to increasing body drag and the start of retreating blade stall. The maximum forward airspeed is that at which the power required intersects with the available engine power.

The maximum safe lateral and rearward airspeeds are restricted by sideslip and pitch back limitations. There may also be additional limitations on airspeed in the forward quadrants due to aerodynamic interaction between main and tail rotors, which may result in inadequate yaw control.

The flight handbooks provided by helicopter manufacturers do not always contain the most useful information concerning the limits of the flight envelope. Some manufacturers may not even provide cross-wind limits. Others provide limits for relative wind along the lateral and longitudinal axes of the helicopter only, whereas

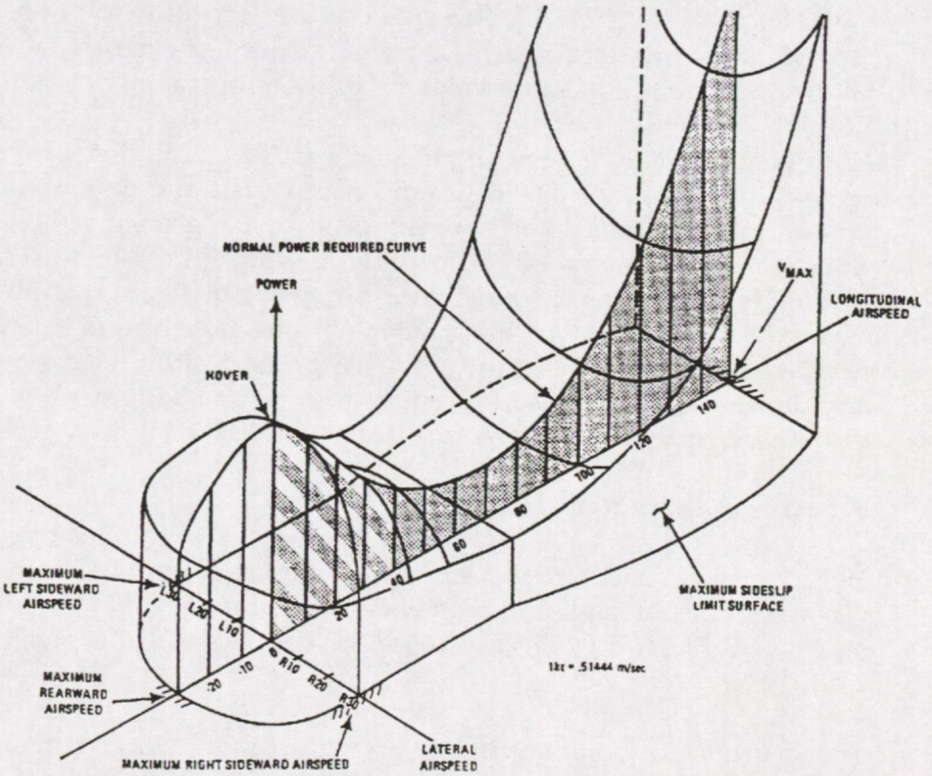



**Figure 7 A three-dimensional helicopter performance envelope**
After Kolwey (1977)

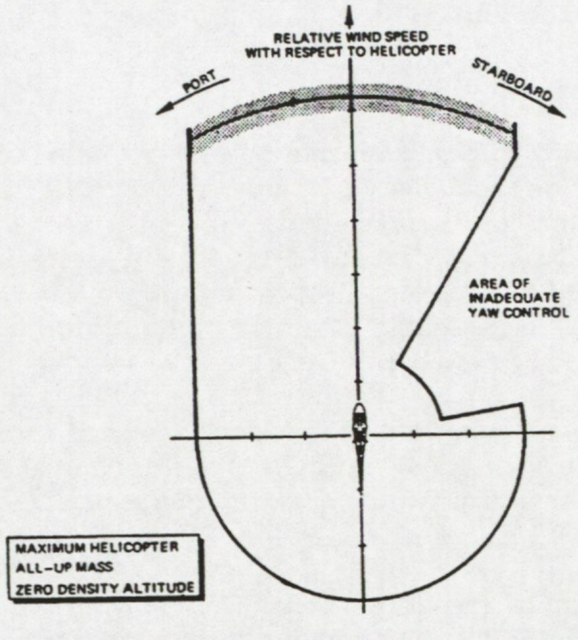



**Figure 8 Relative wind limits for take-off and landing**
After Fang (1991)

at least one manufacturer provides a plot of maximum wind velocity for hovering flight in all directions relative to the aircraft, as in Figure 8. Where information is not provided it must be established by the operators by experience.

Relative wind envelopes, such as that in Figure 8, can be established in ground based hover tests (Fang, 1991), and provide useful information to the pilot concerning the capabilities of the helicopter. A more complete flight performance envelope would provide a numerical basis for limits for offshore operations.

Additional restrictions may need to be applied to the flight envelope for offshore operations (Fang, 1991). In ground based tests the helicopter will be flying in ground effect. A helicopter hovering close to the ground requires less power than when it is hovering several rotor diameters above the ground (Fradenburgh, 1991). During deck landings the helicopter may not benefit from ground effect until it is stationed immediately over the deck. Some helicopters may have difficulty in maintaining a stationary hover out of ground effect at maximum all up mass. Additional power may also be required when operating close to ship due to wind turbulence, as is shown in Figure 9 (Johnston, 1971).

## 3.2 Structural characteristics

Helicopter manufacturers usually define sloping ground limitations. These take into account rotor hub and mast moments (Fradenburgh, 1990), undercarriage geometry and strength, and braking efficiency. The limits are typically of the order of 12 degrees.

The dynamic environment on a ship imposes additional demands on a helicopter due to the motions of the landing deck. In contrast to landings ashore, the rate of closure in a deck landing will be a combination of the vertical velocities of the aircraft and the deck. Helicopter undercarriages are typically designed to withstand vertical touchdown velocities of up to 12 feet per second.

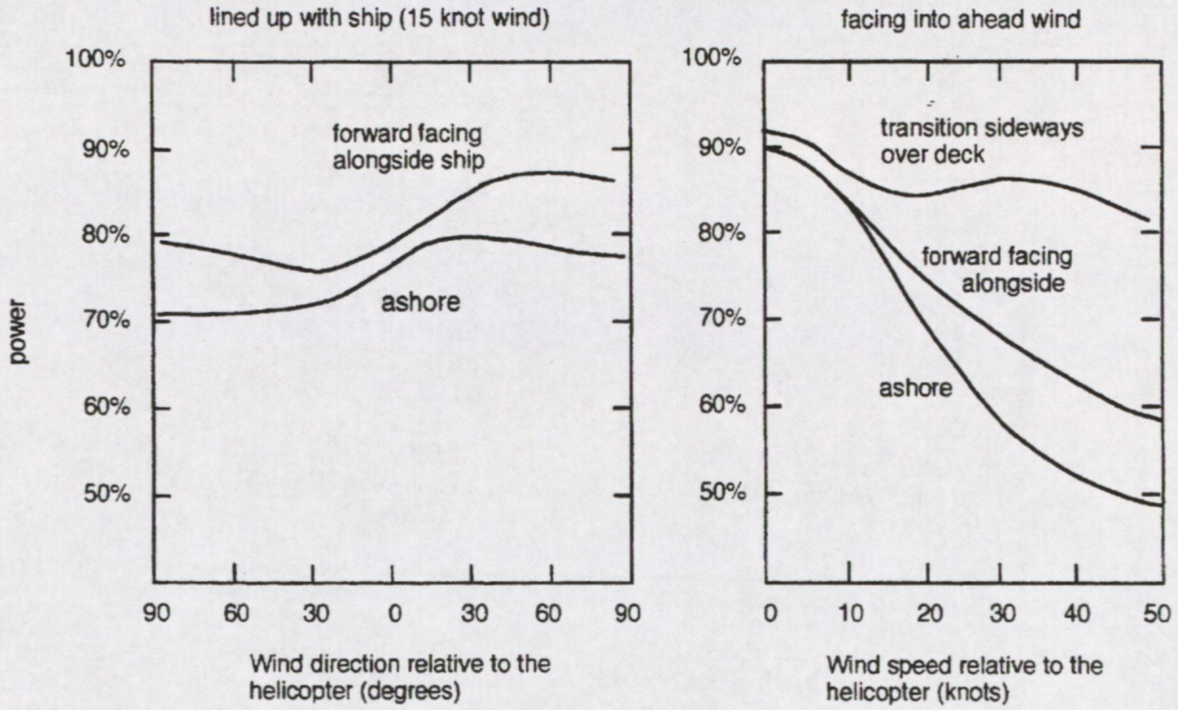



**Figure 9 The effect of turbulence around a deck on the power required for hovering**
After Johnston (1971)

Tuttle (1976) reported results of instrumented landing tests with an SH-2F helicopter, which has a tail wheel undercarriage. The data from these tests demonstrated that a relatively minor asymmetry (in terms of roll attitude and velocity) in the landing could generate individual main gear loads which were considerably higher than those achieved in symmetric drop tests at the same sinking speed and gross weight. The relative lateral velocity between the helicopter and deck was another important factor in the generation of asymmetric undercarriage loads. Tuttle (1976) used a computer simulation to predict sink rates below which there was a positive margin of structural safety. Figure 10 shows a safe landing envelope for an SH-2F helicopter landing on a destroyer in sea state 5 (Tuttle, 1976). This is expressed by sinking speed (relative to the deck) as a function of deck roll angle at touchdown. It can be seen that the safe sink rate is significantly reduced compared with that for a stationary deck, particularly with increasing deck angles.

## 3.3 Helicopter limitations imposed by deck motions

### 3.3.1 *Take-off and landing*

Baitis (1975) measured ship motions, sea and wind conditions during a four day sea trial of an SH-2F helicopter and a U.S. Navy DE-1052 class destroyer. A total of 97 landings were made during the trial in sea states up to a low state 5. Air turbulence, or gustiness, was found to have a greater effect on the relatively small SH-2F helicopter than ship motions, although difficulties were encountered due to ship motions.

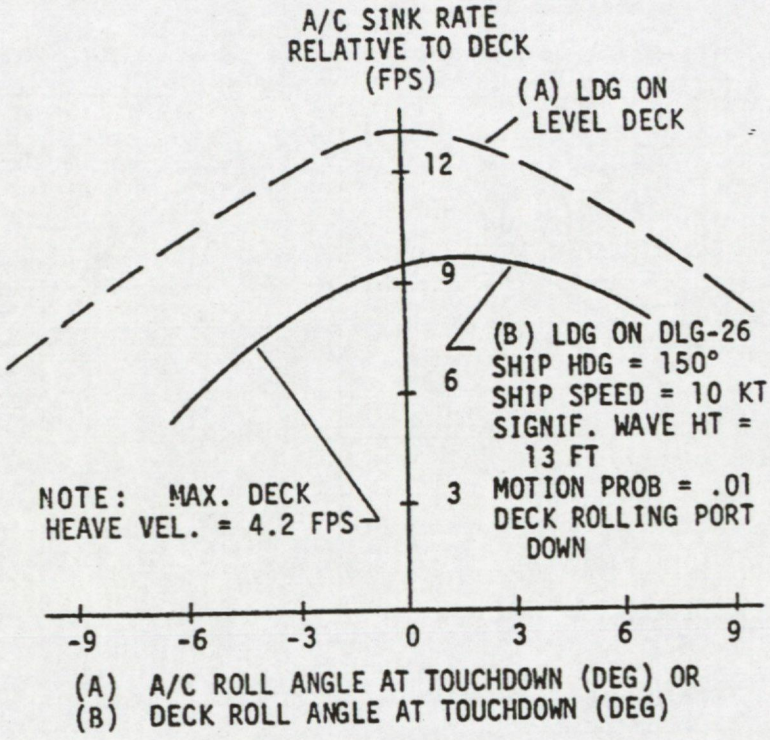



**Figure 10 Predicted safe sink rates for an SH-2F helicopter**
After Tuttle (1976)

The ship responses, h(t), recorded during the above trial included roll and pitch displacement, and vertical and lateral acceleration. Two measures of the ship responses were related to the difficulty experienced during take-off and landing events. The first was the largest double amplitude motion, $H_a$, (see Figure 6) which occurred during the event, and the second was the instantaneous ship response, $h(t_o)$ at the instant of landing or take-off (for a landing event this would be the instant when the helicopter became fully supported by the deck).

The average duration of a take-off event was 9.8 s, but an average landing event took 19.6 s. Take-offs were generally completed within two ship motion cycles, and 46% of take-off events were completed in one cycle. However, some landings required as many as five cycles of ship motion to complete. The double amplitude motions measured during take-off events were also generally lower than those measured during landing events. These results indicate that the pilots found it easier to select an optimum time to take-off, and that less time was spent over the deck during take-off events compared with landings. The author concludes that take-offs are less affected by deck motions than landings. He points out that this does not necessarily mean that pilots are able to select low instantaneous motions in which to perform critical stages of the operation. In fact, the measurements indicated that take-offs often occurred at greater instantaneous pitch and roll angles than did landings. Pilots were not particularly successful at making the instant of either touchdown or lift-off occur when the deck was level, and this may be an indication that the angular inclinations of the deck are less important than other ship responses, such as vertical velocity or acceleration. The largest instantaneous values associated with landings and take-offs were respectively 6.3 and 7.6 degrees for roll, and 1.6 and 1.4 degrees for pitch.

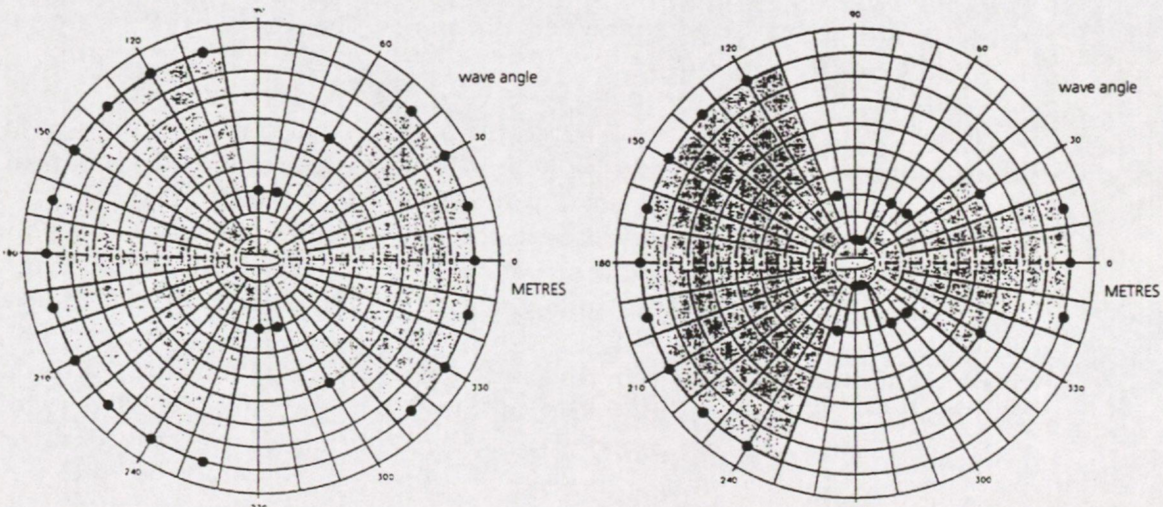
**Table 2 Ranges of motion amplitudes occurring during waveoff events**

| | *Double Amplitude* $H_a$ | *Significant Amplitude* $\bar{H}_{1/3}$ |
|---|---|---|
| Pitch angle (degrees) | 2.7 – 5.6 | 2.2 – 4.0 |
| Roll angle (degrees) | 6.4 – 14.6 | 4.4 – 11.1 |
| Vertical acceleration (g) | 0.17 – 0.31 | 0.13 – 0.25 |
| Lateral acceleration (g) | 0.12 – 0.20 | 0.09 – 0.16 |

Baitis (1975) suggested that limiting motion conditions might be estimated from either pilot ratings of the difficulty of aircraft events, or from cases where the ship motions and other flight conditions were so severe that the event had to be aborted (these aborted events are referred to as 'waveoffs'). It was considered that the waveoff criterion was more reliable for defining the motion levels which limit aircraft operations. Three waveoff events occurred during the trials. Table 2 shows the ranges of pitch and roll angle, and lateral and vertical acceleration which occurred during the waveoff events.

### 3.3.2 *Standing on the deck*

Ferrier *et al* (1991) have modelled the dynamic interface between an EH101 helicopter and a Canadian CPF class frigate. The helicopter was modelled unsecured on the deck, within 20 degrees of the centre line, with rotors spread. Deck safety envelopes were computed, as a function of wave height and direction. The safety envelopes indicate limitations defined by the point at which an aircraft/ship 'incident' was predicted to occur. An incident is defined as the occurrence of aircraft turnover, pitchback, on-deck slide or uncontrolled lift-off. Deck safety envelopes are shown in Figure 11 for a 15 knot ship speed and wind gusting up to 50 knots. Beam




*EH101/CFP 15 knots, dry deck* *EH101/CPF 15 knots, wet deck*

**Figure 11 Deck safety envelopes, as a function of wave height and direction, for an EH101 helicopter and CPF class frigate**
After Ferrier *et al* (1991)

sea conditions can be seen to be the most restrictive, particularly with a wet deck, while following sea conditions were the least restrictive.

The propensity for a helicopter to slide or topple is increased by wind and by vertical and lateral acceleration of the helideck (see Section 2.1.2). Lateral and vertical accelerations will be present on high mounted decks located at the bow or stern. The effects of these factors have been modelled for the U.S. SH-2F helicopter by Wei *et al* (1991), showing the interaction between deck surface condition (see Section 2.4.5.), deck motion and wind. On a worn flight deck, with a coefficient of friction of 0.5, a cross wind of 30 knots decreased the roll angle at which sliding occurred from 19 degrees to 17.5 degrees. A 45 knot cross wind further reduced the sliding threshold to 13 degrees. The combination of a 30 knot cross wind with a –0.2 g vertical acceleration reduced the sliding threshold to 12 degrees, and adding a 0.2 g lateral acceleration reduced the threshold to only 7 degrees.

The above simulation assumed that the rotors were turning. Civil helicopters are loaded and unloaded on the decks of vessels with rotors turning, in order to facilitate emergency take-offs. A turning rotor generates significant aerodynamic lift, even with the collective control at its minimum, and this will tend to reduce the vertical force that the helicopter exerts on the deck.

# 4 INCIDENT AND ACCIDENT REPORTS

The CAA Safety Data Analysis Unit (SDAU) holds records of 'reportable occurrences'. A reportable occurrence is defined as 'an incident, malfunctioning or defect endangering, or which if not corrected would endanger, the aircraft, its occupants, or any other person'.

Seven incidents were reported to SDAU between April 1976 and June 1992 which were a direct consequence of excessive motions after landing on vessels. An additional foreign incident (in the Gulf of Mexico) involved a helicopter rolling off a deck, but the cause was not identified. One incident was caused by the undercarriage hooking under a deck safety net. The above incidents are summarised in Appendix B.

No incidents have been reported to the SDAU in which ship motions have caused a problem during the landing phase. However there is evidence from internal company reports, and anecdotal evidence from pilots (see Section 5.2.1), that ship motions are often under-reported to helicopter crews by ships. These have sometimes resulted in pilots feeling uncomfortable about landing or about remaining on the deck after landing. They have also caused landings to be aborted.

Problems and incidents reported in the landing phase mostly involve unexpected turbulence around the deck. This can be due to the direction of the wind over rig structures, hot exhaust gases, or incorrect reporting of wind speed or direction by vessels.

## 5 HELICOPTER PILOTS

### 5.1 Training and experience

One helicopter company suggested that approximately 30% of its pilots were originally trained in the Royal Navy, 30% in the Army, 10% in the Royal Air Force, and the rest by civil and other organisations. Pilots all receive the same training when they join the companies, regardless of experience. This consists first of conversion to type, followed by off-line training during which deck landings are performed in different weather conditions and in daylight and at night. The range of decks and landing conditions depends on availability of suitable helidecks, and may be confined to mobile rigs operating close to the shore. There then follows 1 to 2 months line training, which consists of acting as co-pilot to a line training captain on regular passenger flights. Experience is thus built up by both observing and performing landings on a variety of decks under supervision.

### 5.2 Pilot opinion

There is a wide spread of pilot opinion concerning the hazardous aspects of deck landings. Some consider that landing on moving decks is a problem that has to be lived with, and that company procedures and limits are conservative enough to make the operation acceptably safe. One common concern is the accuracy and consistency of information passed to them from vessels. The following issues were raised in discussions with pilots in the three helicopter companies currently operating from Aberdeen.

#### 5.2.1 *Reporting of vessel motions*

Some pilots suggested that there is a need for measurement procedures to be standardised, perhaps in the form of instructions or rules issued to all vessels with certified helidecks. It was suggested that the period of time over which the observations are made should be quoted, and that this should be of the order of ten minutes, during which time the heading of the vessel should be constant. It was pointed out that motion estimates should be revised after any change of heading. It was sometimes not clear to pilots if the quoted displacements are the total amplitude, or the excursions either side of an average position. Several pilots reported having landed on decks which were subsequently found to be moving much more than had been reported, causing some discomfort and concern about the safety of the aircraft. One vessel had reported a much smaller heave displacement than was apparent on landing, and it was later discovered that the instrument had been moving through its full scale deflection and the vessel had reported the limits of the scale. On another flight, a vessel had reported the pre-flight roll motion as 2.5 degrees. On the helicopter's approach the vessel revised the figure to 4 degrees. After being advised that the helicopter was being diverted, the radio operator revised the roll amplitude to 2.5 degrees with an occasional maximum of 3 degrees. The helicopter decided that it was safe to land, but on the deck the aircraft's instruments indicated rolls of ±5 degrees. On the return flight a passenger indicated that the vessel had been rolling by up to ±7 degrees before the helicopter's arrival. It was suggested that the reporting accuracy may deteriorate if the vessel's radio operator is due to leave on the flight!

5.2.2 *Vertical motion*

The vertical (heave) velocity of the deck was generally believed to be more important than heave displacement, and it was suggested by one pilot that heave rate limits should be established. Heave rate relates directly to performance margins and control responses, in that the helicopter needs to be able to move out of the way of a deck which moves unexpectedly upwards. The displacement is relevant when determining the best moment to touch down: it is important to land when the deck is near its highest point.

5.2.3 *Angular motions*

High angular velocities of a landing deck were thought to make the landing task more difficult. Horizontal motion accompanying roll and pitch is not believed to be a problem, except when the displacements become large. Loading columns (crane bearing, flexible structures attached to the sea bed) are particularly prone to large and irregular horizontal motions.

5.2.4 *Types of vessel*

Few problems have been reported with the motions of semi-submersibles. Larger free-floating vessels, such as crane barges, can sometimes present landing problems and small ships often present problems. Ship landings were believed to be more hazardous because the deck motions are more rapid and less predictable than those of semi-submersibles. Rear mounted helidecks are prone to corkscrewing motions which were reported to be particularly difficult to assess. Semi-submersibles have slower motions and the larger decks have better clearance margins and better visual references. One pilot suggested that there was a good argument for establishing individual motion limits for each vessel.

One pilot reported that he had experienced problems when vessels have changed course while the helicopter was standing on a deck. It was suggested that course changes should be minimised, in order to maintain minimal deck motions and to ensure that the aircraft does not take off in an unfavourable relative wind.

5.2.5 *Pilot experience*

Recent practice of landing on a moving deck was said to make the task easier. Pilots who are stationed offshore were said to become more proficient and more confident compared to those who are stationed ashore.

5.2.6 *Visual cues*

The landing task was said to be more difficult if there is not a good horizon reference to establish a stable hover, as well as a good landing deck reference. The preferred deck reference was at eye level, or below the helicopter, but the pilot should not have to look backwards.

One pilot suggested that lighting can cause problems in night landings. It was pointed out that lighting should illuminate the deck markings and the surrounding structure, but that there should be no light source pointing toward the helicopter which could cause glare.

Particular visual problems were reported by several pilots when landing in line with the ship's axis on a deck mounted at the bow, due to the restrictive view of the structure of the ship.

#### 5.2.7 *Passenger access*

The moving rotor disc can be dangerous to disembarking and embarking passengers when a ship is rolling and pitching, particularly when the Automatic Flight Control System (AFCS) is engaged. One pilot considered that it is desirable to keep the AFCS engaged in case an emergency take-off becomes necessary, but others suggested that the AFCS should always be disengaged when standing on the deck. A clear access is always needed to the side of the helicopter to reduce the probability of passengers walking under the front of the disc, or near to the tail rotor. If the deck access point is at the front or rear of the helicopter, passengers tend to ignore safety warnings. This makes cross deck landings desirable whenever prevailing wind conditions allow. It was suggested that this problem could be overcome by requiring two access points to all decks, separated by a 120 degree arc.

#### 5.2.8 *Landing Decks*

Deck design may contribute to turbulence hazards. It was suggested that decks are not inspected as often as they should be: deck nets can be found to be not tight, and obstructions (such as aerials) are sometimes erected within the 210 degree free arc.

#### 5.2.9 *Wind turbulence*

Wind turbulence around moving decks presents a double hazard. Turbulence increases workload and decreases power margins. Clad derricks cause particular problems on mobile rigs. The lack of analytical testing results in specific problems only being identified by experience. Smaller vessels are generally free of severe turbulence hazards, unless they are in the lee of other structures.

# 6 PROCEDURES AND LIMITS FOR LANDING ON MOVING DECKS

## 6.1 Military helicopters

### 6.1.1 *Motion limits*

In the Royal Navy, landing conditions for each combination of helicopter and ship type are mapped out on Ship Helicopter Operation Limit (SHOL) plots. The SHOLs are polar plots of wind velocity limits as a function of relative wind direction. Individual SHOLs are derived for combinations of different types of approach and bands of all-up-mass. Each SHOL has associated deck motion limits, in terms of maximum amplitudes of roll and pitch at the time of landing (see Figure 12). The SHOLs are established by making a large number of trial landings, during which recordings are made of engine torque, pedal displacements, handling qualities and ship motions (Finlay, 1991). More analytical approaches for defining SHOLs are being introduced by the Dutch services to reduce the time taken in flight testing at sea (Renirie and Hoekstra, 1979).

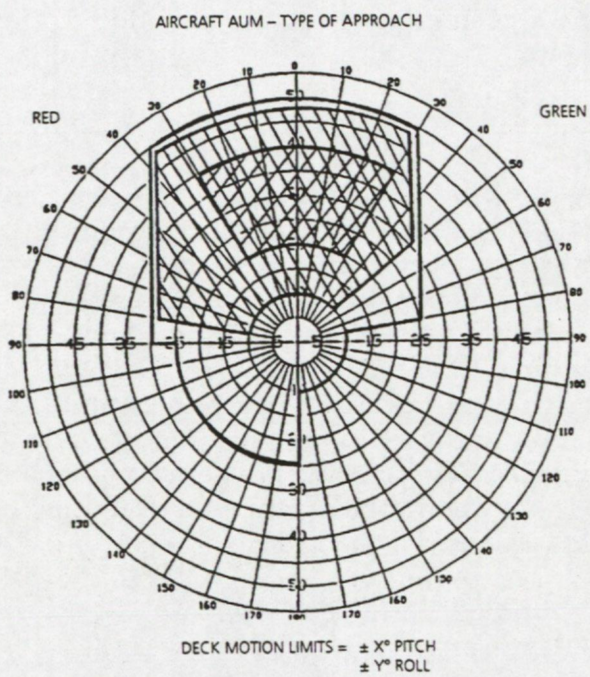



**Figure 12 Typical ship/helicopter operation limits**

The U.S. and Canadian Navies have sponsored research and development of dedicated instrumentation to assess deck motions for landing helicopters. An 'Active Operator Guidance' computer program, running on a personal computer, has been tested for integrating all limiting environmental factors and displaying safe operating limits for carrier-based operations (Baitis, 1989; Pattison and Bushway, 1991). The ship motion is calculated from a model, based on heading, wind and sea state, but is being updated to interface with on-line motion transducers. The program is currently being extended to include limits based on the probability of a helicopter sliding on the deck, based on procedures proposed by Graham *et al* (1991).

The Landing Period Designator or LPD (O'Reilly, 1987; Ferrier *et al*, 1991) is a device which computes the 'energy index' of the helicopter landing deck. The energy index is a function of displacement and velocity in roll and pitch, and velocity and acceleration in heave (z-axis) and sway (y-axis). The energy index is continuously calculated and displayed to the pilot via an array of coloured lights. When the index is low the ship is stable and the deck displacements and accelerations are benign. The LPD is intended to reduce the pilot workload by indicating the most appropriate times to initiate safe landings or take-offs.

### 6.1.2 *Landing procedures*

The Royal Navy generally perform forward facing landings (i.e. with the longitudinal axis of the helicopter lined up with that of the ship). The helicopter arrives in the hover alongside the flight deck, preferably on the port side to optimise the pilot's view of the deck. The aircraft is then transitioned sideways to hover over the landing spot before executing a vertical landing. The hover height above the deck is normally 4 to 6 metres.

If the ship is not heading into the wind, and the cross axis wind limitations of the helicopter are exceeded, the helicopter may approach the ship along the relative wind vector. The helicopter hovers alongside the deck facing into wind before transitioning forward over the landing spot and making a vertical landing. The aircraft may land facing in any direction, depending on the physical clearances available on the deck.

### 6.1.3 *Securing and handling a helicopter on the deck*

Naval ships have trained and disciplined crews available to assist every phase of the landing, including lashing the helicopter to the deck immediately after touch down. Naval helicopters such as the Westland Lynx are optimised for operations from small ships, and are equipped with facilities such as negative pitch, to provide downward thrust to hold the helicopter steady on the deck during the securing operation. Automatic securing systems such as the 'harpoon' deck lock (Reimering and Craig, 1989) or the RAST active winch down system (Wigotsky, 1984) may also be available.

## 6.2 **Civil helicopters**

### 6.2.1 *Motion limits*

All three companies currently operating from Aberdeen require that landings should not be attempted on offshore floating helidecks when the deck is moving outside specified roll and pitch displacement limits. Table 3 shows roll and pitch limits for daylight operations which were in force in December 1992. The three companies have similar pitch and roll limits for the AS332L Super Puma helicopter. Bristows and Bond specify roll and pitch limits of ±3 degrees for day and night time landings. BIH allow landings on decks with up to 6 degrees total movement around the vertical axis, with a maximum deck inclination of 5 degrees from the horizontal, but maximum deck inclination is reduced to 3 degrees at night. BIH also specify a lower night time limit of 2 degrees either side of the mean for fully floating helidecks (i.e. untethered ships) at night. Bristows specify a heave (vertical) displacement limit of 10 ft, but this is not strictly enforced. BIH and Bond do not impose heave limits but the Bond operations manual states that commanders should be conscious of the rate of heave, particularly when the reported heave displacement exceeds 12 ft. The BIH operations manual states that heave must be assessed by the captain prior to landing, and that the rate of heave should be the main consideration rather than the amplitude.

**Table 3 Typical roll and pitch motion limits (degrees) for daytime operations**

| | *BIH* | *Bond* | *Bristows* |
|---|---|---|---|
| AS332L | ±3 | ±3 | ±3 |
| S76 | ±5 | ±4 | ±2.5 |
| S61 | ±3 | | ±3 |
| Bolkow 105 * | | ±5 | |
| SA365N | | ±4 | |

* Fitted with a skid undercarriage

There is more variation between motion limits shown in Table 3 for the smaller, S76 helicopter. Up to the end of 1992, Bond specified displacement limits of ±4 degrees in pitch and roll for both day and night operations. BIH specified up to 10 degrees total movement in any axis with a maximum inclination in any axis of 7 degrees from the horizontal, reducing at night to 8 degrees total movement with a maximum inclination of 5 degrees. BIH imposed a lower night time limit for fully floating helidecks of 2 degrees either side of the mean inclination. Bristows' motion limits for the S76 were ±2.5 degrees in roll and pitch and 10 ft in heave, reducing at night to ±1 degree and 5 ft. The lower limits imposed by Bristows may reflect the lower proportion of operations flown to floating decks (a large proportion of flights to fully floating decks are flown by the S76), compared to the other two companies. About 15 to 20% of Bristows flights are to moving decks, including some ships. About 10% of Bond flights and 5% of BIH flights are to ships, with the rest of each company's operations equally split between mobile rigs and fixed platforms.

The AS332L and S76 were the only types that were operated by all three companies. BIH has now (July 1993) ceased to operate the S76. Bristows have made some revisions to their limits for this aircraft, specifying ±2.5 degrees for rear-mounted decks on small ships and ±2 degrees for front-mounted decks. The limits for semi-submersibles and large ships are ±4 degrees. It is understood that Bond have revised their limits for landing S76 helicopters on small ships accordingly.

The S76 has a wider undercarriage relative to the height of the centre of gravity and it is therefore potentially more stable when standing on a deck. However it is significantly lighter than the AS332L and may be more affected by high winds. In interviews with pilots, concern was expressed about the braking efficiency of the S76 compared with the AS332L. In the hover, the fuselage of the S76 is pitched up by 5 degrees or more, reducing the deck edge tail clearance, which may be a problem with large angular deck motions. The S76 has a low rotor disc, resulting in a greater clearance hazard to personnel on the deck, particularly at the front of the helicopter. The S76 is smaller and potentially more agile, but the AS332L has a much larger power margin in the hover, particularly at high all up mass.

### 6.2.2 *Other operational restrictions*

BIH requires that night landings on fully floating vessels may only take place when there is a clearly visible horizon, or where other stable illuminations are visible in the normal line of sight during the final approach and landing to provide satisfactory attitude cues.

The operators also apply weight restrictions when landing with certain wind directions on vessels with known turbulence hazards.

### 6.2.3 *Landing procedures*

Helicopter companies have traditionally enforced a requirement to minimise the time when the aircraft is at risk due to engine failure. Therefore hovering at low altitude over the water was discouraged. Companies now appear to be more relaxed about this requirement, and pilots give more priority to assessment of the deck motions, and to clearing obstructions with adequate margins.

The helicopter normally establishes a high hover above the deck, from which the pilot assesses the deck motion so as to land when the vessel is at the top of its vertical displacement. If the motions are large or unpredictable, or if access is restricted into relative wind, the helicopter may hover alongside the deck to provide a better view of the ship motions. If the pilot considers the deck motion to be acceptable, the helicopter will transition over the deck and land during a quiescent period. Different conditions apply to each landing, and different landing techniques are appropriate in different circumstances.

Most pilots prefer to land into, or within 20 degrees of, relative wind. Some will accept cross winds, within the limits of the helicopter, to optimise passenger access (see Section 5.2.7) or visual cues (see Sections 5.2.6 and 2.4.6).

#### 6.2.4 *Securing and handling a helicopter on the deck*

A helicopter is vulnerable to the forces generated by deck motions and other sources while it is partially secured to a deck. The aircraft may still be susceptible to sliding and toppling, but is unable to make an emergency take-off to avoid the consequences of an unexpected deck motion. If the helicopter is to be secured to a moving deck the operation must be carried out quickly and efficiently. Crews of civil vessels are not generally available for, or trained in, lashing aircraft, so this is avoided unless the engines are to be shut down.

## 7 DISCUSSION

### 7.1 Accuracy of pitch and roll measurements

All vessels with helidecks are equipped with pitch and roll indicators, although these vary from simple mechanical inclinometers to electronic vertical reference systems. A mechanical inclinometer responds to horizontal accelerations in addition to rotational displacements. The resulting errors will be dependent on the characteristics of the sea, in addition to the heading, loading and characteristics of the vessel, hence it is not possible to apply a simple correction factor. However, provided that the inclinometer is located above the centre of rotation of the vessel and the yaw and sway motions are small, which will almost always be the case, the roll and pitch inclinations will be overestimated. This will result in a conservative comparison with the helicopter landing limits, which are stated in terms of pitch and roll angles.

### 7.2 Effects of horizontal accelerations on sliding

Large angular inclinations may result in helicopters tipping or sliding on the deck. Modelling work has shown that a typical helicopter is unlikely to tip at deck angles below 20 degrees, even with a significant crosswind. Sliding may occur at smaller angles than this, depending on the condition of the deck, wind speed and angle, and the translational accelerations in the plane of the deck (Wei *et al*, 1991). With a tyre/deck coefficient of friction of 0.5 and a 30 knot crosswind, a helicopter has been shown to be in danger of sliding at a deck angle of 17.5 degrees. However, the sliding threshold was shown to be reduced to 12 degrees by a lateral acceleration of 0.1 g, and to 7 degrees by a lateral acceleration of 0.2 g. The lateral acceleration increases with the height above the centre of rotation of the vessel. The centre of rotation is approximated by the metacentre, which is close to the centre of gravity (see Section 2.1.4).

The apparent acceleration in the plane of the deck is a better predictor of the sliding threshold than the angular inclination, since it includes both the horizontal acceleration of the deck and the apparent acceleration due to the inclination relative to the gravitational vector. Assuming that the yaw and sway motions of the vessel are small, the apparent lateral acceleration, $\ddot{s}_{ay}$ can be approximated by (see Section 2.1.1):

$$\ddot{s}_{ay} = g.r_x - Z.\ddot{r}_x$$

Where $r_x$ is the roll displacement, Z is the distance above the centre of rotation and g is the gravitational constant. For a regular roll motion with a period of T seconds:

$$\ddot{r}_x = \frac{-4\pi^2}{T^2}\ r_x$$

Hence the apparent lateral acceleration of the deck on a vessel with a typical roll period of 10 seconds will be given by:

$$\ddot{s}_{ay} = (9.81 + 0.39\ Z)\ r_x$$

The apparent lateral acceleration on a typical ship can therefore be expected to increase by approximately 40% for every 10m above the centre of rotation. Since the helideck on a ship is unlikely to be mounted more than 10 to 15 m above the metacentre, the propensity of a helicopter to slide on the deck is unlikely to be more than 50% greater than that predicted by measurement of pure roll motion. Shorter periods of roll would result in larger increases in lateral acceleration with height, however the predominant roll period of many vessels is longer than 10 seconds, particularly when operating with fin stabilisers. Longitudinal acceleration may increase more rapidly with height above the centre of rotation, since on a conventional ship the pitch period tends to be shorter than the roll period, however the pitch amplitude is generally smaller than the roll amplitude.

The roll and pitch limits set by the helicopter operators are probably conservative enough to take into account the effect of horizontal accelerations on the sliding threshold. None of the incident reports presented in Appendix B suggest that difficulties are likely to be encountered when vessels are rolling within limits set by the operators in the North Sea area.

## 7.3 Reporting of motions by vessels

A lack of consistency has been noted in the reporting of motions by vessels. Although differences in the instrumentation available on different vessels may make some contribution to this problem, the observation and reporting of the measurements is likely to be a more important source of variability. Problems with reporting procedures may include confusion of single amplitude motion and double amplitude motion, changes of course, and observations being made over an inadequate period of time. These sources of variability might be reduced by the provision of guidelines for the observation and reporting of roll and pitch motions, as indicated by current instrumentation.

Vessel motions have sometimes been observed to increase beyond landing limits during the period that a helicopter is standing on a deck. Roll and pitch motions are narrow-band random processes, and the amplitudes vary with time. Hence observations made over short periods may not be representative of the motions which occur during the time a helicopter takes to land, unload and load passengers and freight, and take-off. This may be of the order of ten minutes. It is therefore important that the measurements of vessel motions take into account the statistical properties of the motion, in order to minimise the probability that the limits will be exceeded within the time that a helicopter is likely to remain on the deck. The primary requirement should be to observe the maximum roll and pitch excursions either side of the vertical over defined periods of time. During the observation period, the ship should maintain the steady course and speed which is expected to apply when the helicopter lands. Since deck motions are dependent on the heading and speed of a vessel, as well as the sea conditions, it is important that the helicopter operator is made aware of the conditions under which the reported ship motions were observed. The helicopter crew may then be aware, when they arrive at the vessel, whether the conditions have changed since the magnitudes of the motion were reported.

In addition to maximum roll and pitch angles, it may also be helpful to report estimates of average (significant) amplitudes. The landing limits may then be compared with either the maximum roll and pitch angles, or with 1.6 times the reported significant amplitudes, whichever are greater. It can be determined from the Rayleigh distribution that $1.6\bar{h}_{1/3}$ can be expected to be exceeded only once in every 500 cycles of ship motion (see Section 2.3). The length of the measurement period will be a compromise between the confidence which is required in the data, and the time which can be devoted to the observations. To establish the relationship between statistical confidence and the length of observation it would be necessary to make long term recordings of ship motions on representative vessels. Such measurements would also enable other statistical techniques to be investigated, with the aim of developing low-cost automated methods of measuring ship motions for comparison with helicopter landing limits.

Ships are currently required to report vertical (heave) amplitudes, but only one company currently retains landing limits for heave motion. The vertical velocity of the deck is recognised to be an important factor in landing safety, but numerical limits cannot be imposed because ships are not equipped to measure this motion. The peak velocity (in $ms^{-1}$) may be estimated by dividing the double amplitude heave displacement (in metres) by twice the period (in seconds). The additional reporting of the period of the heave motion, which is dependent on the characteristics of the ship and the seaway, could provide a numerical basis for estimating heave velocity. This would assist the eventual establishment of velocity limits.

### 7.4 Objective measurements of motion statistics

More reliable and objective measurements of statistical averages, which require observations to be made over long time periods, could be made by the use of electronic instrumentation. Low cost instrumentation suitable for measuring deck motions could consist of a tri-axial accelerometer mounted at the centre of the helideck. The accelerometer could be combined with an analysis system based on personal computer technology. Such an instrument could calculate the angular displacements and estimate the statistical parameters of the deck motions, providing values which could be compared with existing helicopter limits. It would also enable limits to be established in terms of the accelerations and velocities in the plane of the deck and their derivatives, which can provide a less ship-dependent indication of the risks of sliding and other landing hazards than measurements of angular inclination. Software suitable for operating the instrument could be assessed using long-term recordings of representative ship motions. Further research may make it possible to combine the deck motions in each axis, and their derivatives, into a single motion index of the probable effect of the motions of a vessel on helicopter landing and stability on the deck (e.g. Ferrier *et al*, 1991).

### 7.5 Provision of helicopter performance data

Few helicopter performance data are provided by manufacturers: operators are only able to establish limitations by experience. Low airspeed performance envelopes can be established in ground-based hover tests (Kolwey, 1977; Fang, 1991), providing a numerical basis for the establishment of limits for offshore operations based on motion descriptors (see Section 3). The provision of relevant information could be encouraged by the establishment of guidelines defining the minimum information which should be presented in the flight manual for helicopters making landings on moving decks. This information may include the relative wind limits in all quadrants at a range of weights, as well as realistic sloping landing limitations in both longitudinal and lateral axes.

## 8 CONCLUSIONS

8.1 Civil helicopter operators specify deck motion limits for their aircraft in terms of roll and pitch displacements. Ships are required to report vertical (heave) amplitudes, but only one company currently retains landing limits for heave motion. The vertical velocity of the deck is recognised to be an important factor in landing safety, but it can only be assessed visually by the pilot.

8.2 Instrumentation for measuring pitch and roll varies from simple mechanical inclinometers to electronic vertical reference systems. Vertical reference systems can be expected to give an accurate indication of angular displacements at the dominant frequencies of ship motions. Mechanical inclinometers are sensitive to horizontal accelerations, and overestimate roll and pitch inclinations, depending on their location relative to the centre of rotation of the ship.

8.3 Large deck motions may cause helicopters to slide on the deck after landing. The horizontal accelerations in the plane of the deck are better predictors of the propensity of a helicopter to slide than the angular inclinations. The horizontal accelerations increase with the height of the deck on the ship and depend on the periods of the motions.

8.4 There is a lack of consistency in the observation and reporting of motions by vessels. Problems with reporting procedures may include confusion of single amplitude and double amplitude motions, changes of course, and observations being made over an inadequate period of time.

8.5 Few helicopter performance data are provided by manufacturers: operators are only able to establish limitations by experience.

## 9 RECOMMENDATIONS

9.1 Standard procedures should be established for reporting ship motions to helicopter operators. The procedures should be compatible with current shipboard instrumentation and helicopter motion limits. Observations available to the helicopter should include:

(a) the maximum roll and pitch amplitudes either side of the vertical;

(b) the mean inclination, or list;

(c) the average (significant) roll and pitch amplitudes;

(d) the vertical displacement of the helideck, and the average period of the vertical motion;

(e) the heading and speed of the vessel during the measurements.

9.2 Recordings of ship motions should be made on representative vessels to establish the relationship between the statistical confidence of the measurements and the length of observation.

9.3 Low-cost instrumentation should be developed to make standardised and automated measurements of motions at the centre of the helideck, and to calculate and display the relevant statistical parameters of the deck motions.

9.4 Procedures should be investigated for computing an index of the severity of deck motions, relative to helicopter landing and stability, which is less dependent on the characteristics of individual vessels than angular displacements.

9.5 Guidelines should be established for the minimum information to be presented in the flight manuals of helicopters making landings on moving decks.

9.6 The effect of deck nets and wheel chocks on the propensity of a helicopter to slide on the deck should be investigated and modelled.

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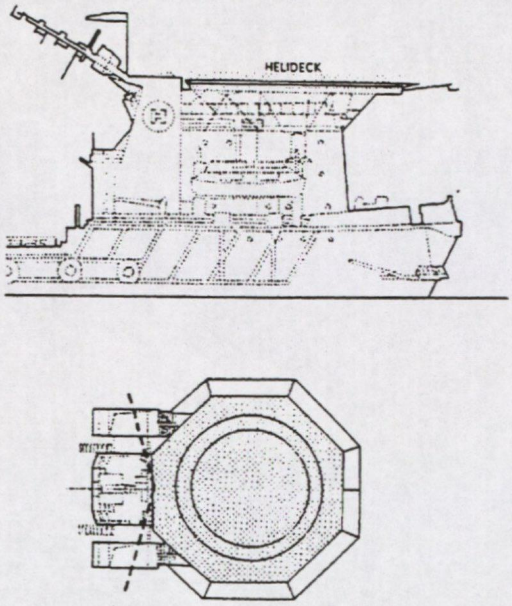
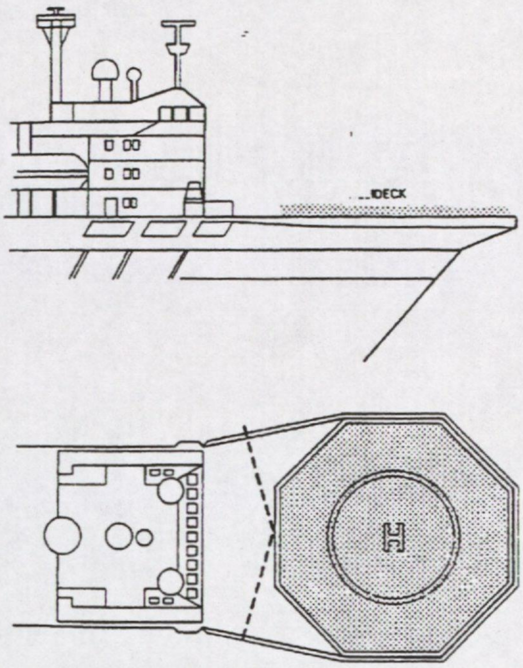
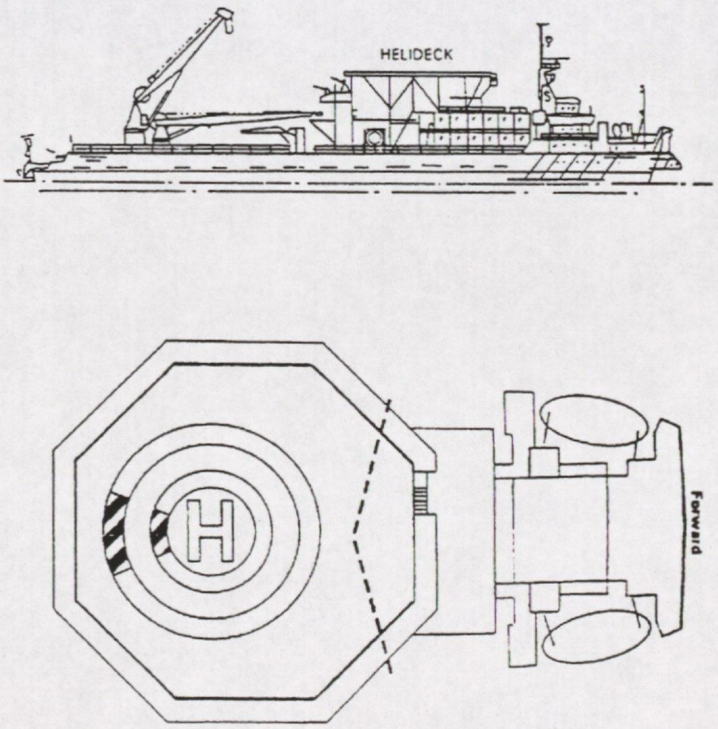
## Appendix A Typical Helideck Locations
After AERAD (1992)



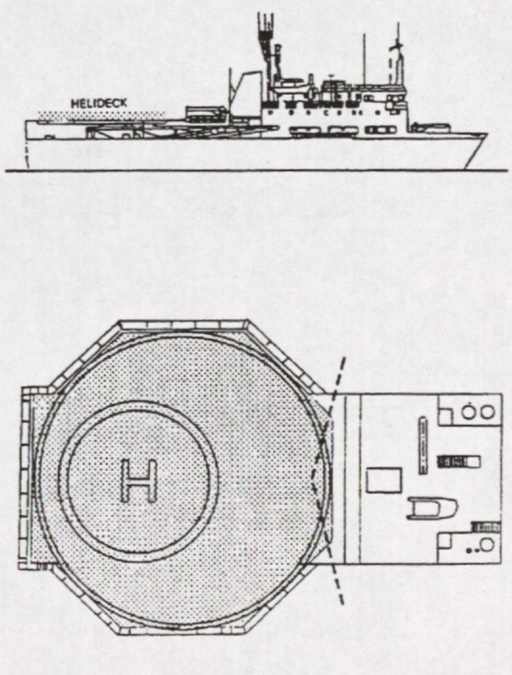

Diving Support Vessel with high bow-mounted deck



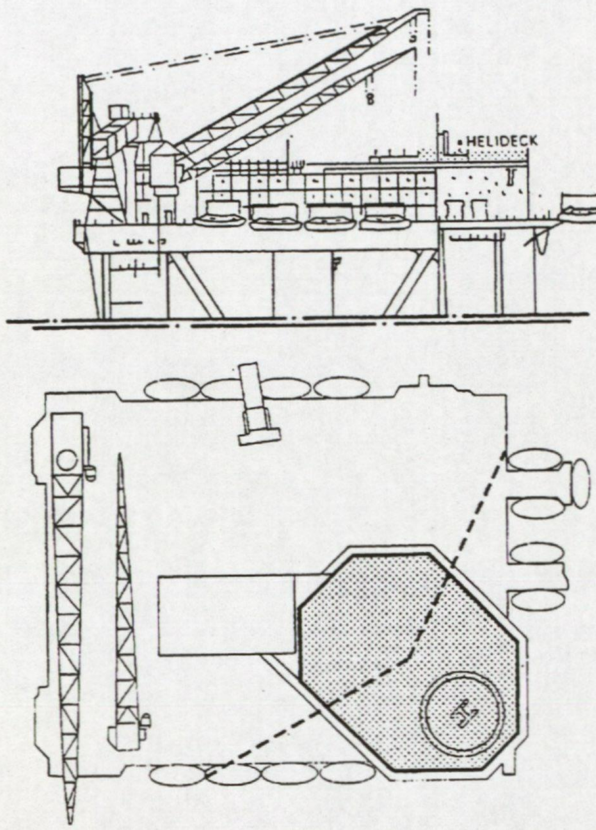
Diving Support Vessel with low bow-mounted deck



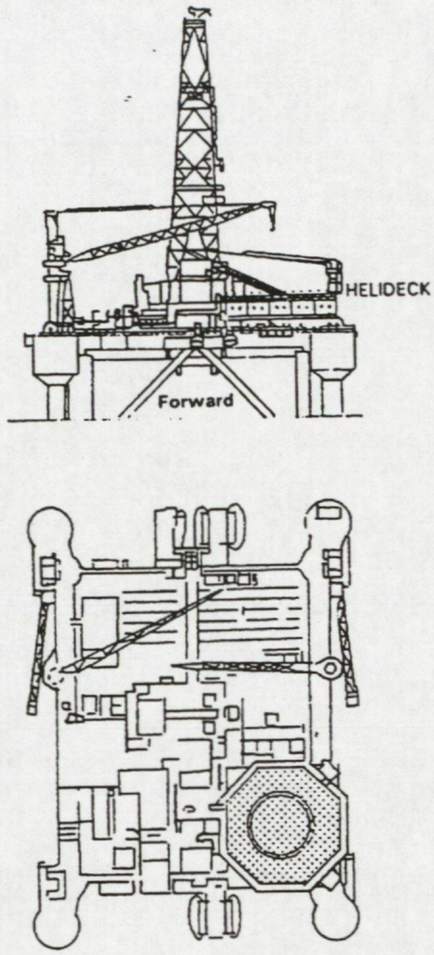

Multi Support Vessel with high mid-mounted deck



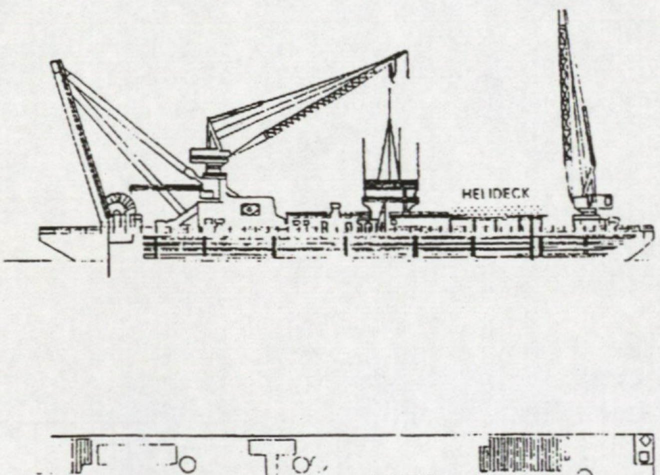

Seismic Vessel with aft-mounted deck




Semi-submersible Flotel




Semi-submersible drilling rig




Crane Barge with low mid-mounted deck

# Appendix B Summary of reportable occurrences

## 1 OCCURRENCES CONSEQUENT ON DECK MOTIONS AFTER LANDING

### 1.1 Occurrence number 7602154H

*Aircraft Type:* Sikorsky S61.
*Vessel type:* Barge.
*Pilot's report:* The vessel is ship type barge with a small helideck and obstructions fairly close to the deck. The barge advised pitch and roll was 1 – 2 degrees; however the landing was quite difficult and shortly after disembarking passengers and freight, the aircraft started to slide on the deck as roll and pitch built up. The roll and pitch subsided, then built up again, and the aircraft again slid on the deck. As the deck is small there is a strong possibility of the tail wheel going over the edge. Therefore an immediate take-off was made.

### 1.2 Occurrence number 7601646C

*Aircraft Type:* Sikorsky S61.
*Vessel type:* Barge.
*Pilot's report:* On approaching the vessel (5 minutes before landing) the barge gave their roll as 1 to 2 degrees. On short finals we realised the barge was rolling excessively. We queried the roll and the barge then admitted to rolling ±7 to 12 degrees. After landing on the Brent B and refuelling we returned to the vessel. By this time it had headed into wind and gave 3 degrees roll. We landed, however whilst on deck the barge broached to and began to roll excessively.

### 1.3 Occurrence number 7602268D

*Aircraft type:* Sikorsky S61.
*Vessel type:* CIL vessel.
*Pilot's report:* Pitch was given as 2 degrees, roll as 2 – 3 degrees with heave 6 ft. The net on the vessel's deck is too small for S61 operations and no effort was made to chock the aircraft. After landing the roll built up rapidly to approx 5 degrees and I felt the aircraft was in danger of slipping on the deck. The deck crew were clustered around the cargo door and dangerously close to the aircraft in case an emergency take-off was made.

### 1.4 Occurrence number 8302943E

*Aircraft type:* Sikorsky S61.
*Vessel type:* Oil rig.
*Pilot's report:* Having landed on vessel within limits of pitch, roll and heave, after approximately 1 minute vessel began to roll rapidly to port and starboard exceeding limits and aircraft was forced to lift off from the deck with airstair door open.

1.5 **Occurrence number 8600309G**

*Aircraft type:* Bell 214ST.
*Vessel type:* Supply ship
*Pilot's report:* Having received reports of 4 degrees roll, 1 degree pitch and minimal heave, a landing was made on the supply vessel for the Magnus platform. Co-pilot left a/c to supervise disembarkation and embarkation of passengers. Shortly after, a roll of 11 degrees and pitch in excess of 6 degrees was experienced, causing aircraft to move laterally across helideck (with one main wheel off the deck), approximately 3 to 4 ft. At the same time, aircraft yawed 30 degrees either side of the original heading, made worse by the lack of a nose-wheel steering lock. The wheels were chocked before the incident occurred. Excessive cyclic control was required to prevent aircraft from toppling over. The danger to passengers and crew beneath main rotors or in vicinity of tail rotor is obvious.

1.6 **Occurrence number 8900540F**

*Aircraft type:* Sikorsky S61.
*Vessel type:* Semi-submersible flotel.
*Pilot's report:* Came alongside the vessel in hover at 60 kt. Assessed rig movement. This was such that I had difficulty maintaining a hover to land. However this was achieved. The deck was moving fore and aft and yawing. Whilst on deck the aircraft rolled back approx 1 – 2 ft. This was checked by brakes and forward cyclic. Chocks inserted. The combination of pitch and roll and turbulence from the deck edge was most uncomfortable.

1.7 **Occurrence number 9201223X**

*Aircraft type:* Sikorsky S76.
*Vessel type:* Support vessel.
*Pilot's report:* Landed to drop 1 and pick up 1 passenger. Whilst on deck the sea state increased and the roll became quite violent. On rolling to port the aircraft moved backwards approximately 1 metre. The H.L.O. who was stood at the nose of the aircraft was struck on the head by the main rotor blades. We indicated to the deck crewman to get clear, then vacated the deck and moved across and shut down on the Heather A platform.

2 **OCCURRENCES POSSIBLY DUE TO DECK MOTIONS**

2.1 **Occurrence number 8504459H**

*Aircraft type:* Sikorsky S76.
*Vessel type:* Drilling rig (foreign incident in the Gulf of Mexico).
*CAA Narrative:* After touch-down aircraft rolled off rig and landed inverted in water. Aircraft had just landed on drilling platform when it rolled backwards and rear wheel caught in a safety net. The pilot attempt to lift off but the wheel would not release causing aircraft to flip over and fall 100 ft into the water.

## 3 OCCURRENCES INVOLVING DECK NETS

### 3.1 Occurrence number 8301156X

*Aircraft type:* Bell 212.
*Vessel type:* Ship.
*Pilot's report:* Helicopter landed normally on the deck of vessel, with a possible slight movement to the left. Passengers taken on board and signal for take-off given. Before lift off the vessel's movement was given attention to get airborne as the ship had a downward movement. Decision for take-off made, and as helicopter became airborne a sudden pitch forward and roll to the right was felt and tried to counteract with aft/left cyclic input. This had no effect and collective was lowered abruptly since helicopter was out of control. Helicopter hit the deck on the right side. Substantial damage to the helicopter.

*Supplementary report:* Tow-ring attached to the inside of the right skid became snagged in a strand of the helideck net. On lift-off, the helicopter nosed down, rolled to the right and crashed onto the deck.