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Naval Architectural Considerations in the Design of a Helicopter

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Methods and procedures are given that have been adopted and/or developed to analyze helicopters with respect to survival at sea in case of an emergency ditching. The areas considered are intact and damaged stability, waterborne motions, and impact loads. Stability of the helicopter is analyzed by applying the criteria for ships and advanced vehicles of several ship classification societies and the U.S. Navy. Waterborne motions are determined by the strip theory and superposition techniques common in naval architecture. Several procedures developed for predicting impact loads are considered with respect to applicability to helicopters. In conclusion, it is shown that the existing theories and criteria for ship vehicle stability, motions, and impact loads can be applied to helicopters on the sea surface to obtain a measure of their survival capabilities, to develop design information for systems intended to be activated under such conditions, and to give pilots more information regarding operation in this mode.

Nomenclature

A_1	= area bounded by heeling and righting-arm curves from maximum roll angle θ_R to second intercept
A_2	= area under righting-arm curve from zero angle to maximum roll angle θ_R plus area under heeling-arm curve between the same angular bounds
a	= half breadth
d	= width of bilge keel
E	= distance between helicopter water plane and forward blade tip
H	= height of linear seakeeping process
$\overline{H^2}$	= the mean square of H
h	= relative distance
N_{IPH}	= immersions per hour
P_i	= probability of immersion
RMS_{rm}	= rms relative motion
RMS_{rv}	= rms relative velocity
x,y	= body axis coordinates: y vertical, x horizontal
$\bar{x},\bar{y}$	= Earth axis coordinates: $\bar{x}$ horizontal, $\bar{y}$ vertical
Z_0	= heave
ζ	= total vertical motion
η	= wave amplitude
θ	= body pitch angle, rad
θ_R	= maximum roll angle
λ	= wave length
ρ	= water density
ω	= wave frequency, rad/s

Introduction

THIS paper describes the methods and procedures that were adopted and/or developed to determine the waterborne performance of a helicopter during emergency ditching modes. The scope encompasses intact and damaged stability, motions, and structural impact pressures.

It is useful to determine the waterborne motions of the helicopter from the standpoints of determining accelerations for structural design, analyzing passenger transfer into rafts launched from the helicopter, and the probability of immersing certain locations or machinery. The waterborne motions or seakeeping analysis of the helicopter is performed by a frequency domain strip theory and superposition analysis common in naval architecture. Methods are given for estimating the effects of added mass and damping of extended wheels.

The intact and damaged stability are considered by adopting the procedures for ships of various classification societies and the U.S. Navy. In the case of the latter, the seakeeping results for roll are directly incorporated. In considering the structural impact loads while landing, a literature survey was conducted to determine the alternative procedures available for estimation of the loads. The adaptability of these procedures is then identified by considering their applicability to the characteristics of a helicopter.

Waterborne Motions

General

The only quantitative requirements for the consideration of helicopter performance in a seaway are the British Civil Airworthiness Requirements.[1] These basically indicate that the flotation and trim characteristics be investigated for sea states 0-7 approximated by regular waves of varying height/length ratios. The only criterion for performance is that the helicopter not capsize.

In predicting performance either model tests or analytical predictions can be utilized. The analytical technique[2,3] considered herein is a statistical frequency domain irregular-wave analysis from superposition of the regular-wave response of a strip theory model of the helicopter.

The motion response output is used to give an indication of the absolute acceleration, rolling displacement, and event exceedance. The absolute motion accelerations is important from structural and comfort standpoints. The rolling displacement is also important in the analysis of dynamic stability. The event exceedance is important in determining the immersion of blade tips and hatches. When the blades are under power, the former can lead to blade failure and subsequent hull failure and the latter can hinder evacuation of personnel onto rafts, if this is intended.

Motion Analyses

The motion predictions require that the mass, damping, buoyancy stiffness characteristics of the helicopter be known.

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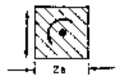
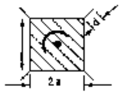
Table 1 Mass properties of a square in an infinite fluid with and without bilge keels

Direction of motion, axis of rotation	Cross-sectional forms	Hydrodynamic mass per unit length, $\pi\rho a^2$	Hydrodynamic moment of inertia per unit length, $\pi\rho a^4$
	Square	$=1.51$	$=0.234$
	$d/a=0.05$ $d/a=0.1$ $d/a=0.25$	$=1.61$ $=1.72$ $=2.19$	$=0.31$ $=0.4$ $=0.69$

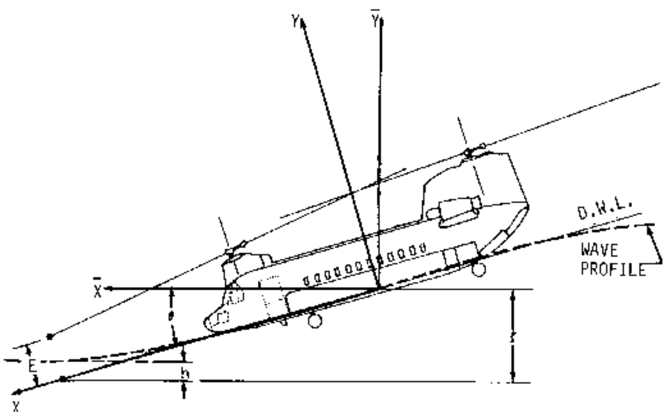


Fig. 1 Coordinates for relative motion.

The cross-sectional and length/beam characteristics of most helicopters are such that strip theory and added mass and damping for ship-like cross sections can be utilized. However, if the landing wheels are extended, their size is generally such that the hydrodynamic effects should be included. To this end the hydrodynamic added mass and mass moment of inertia for a rectangle with corner plates is utilized[4] (see Table 1). It can readily be seen that for cross sections with wheels, the effects on added mass are moderate (13.9% increase for $d/a=0.1$), while those on mass moment of inertia are large (70.9% increase for $d/a=0.1$). Free-surface effects are accounted for by dividing the added mass and roll moment of inertia in half.

The damping due to the extended landing wheels can be determined by considering them as bilge keels and utilizing available empirical formulas for predicting the effects.[5]

Event Exceedance

The classical approach to the statistics of seaway and seakeeping response has been to assume linear processes that are normally distributed. Further, various investigators have shown that the heights of linear seakeeping processes follow a Rayleigh distribution. The Rayleigh probability density function of a random variable H is:

$$P(H) = \begin{cases} (2H/\bar{H}^2)\exp(-H^2/\bar{H}^2) & H \geq 0 \\ 0 & H < 0 \end{cases} \qquad (1)$$

Given the Rayleigh distribution, the probability that the heights of seakeeping events such as waves, motions, and accelerations will exceed a value x is[2]:

$$P = \int_x^\infty \frac{2y}{H^2}\exp(-y^2/H^2)\,dy = \exp(-x^2/\bar{H}^2) \qquad (2)$$

Equation (2) can be used to find exceedance of absolute motions. Another use is to determine the exceedances of certain events that may be described by relative motions. For the immersion of helicopter blade tips, using the coordinate system of Fig. 1, the heave at x is:

$$\zeta = Z_0 - \theta X \qquad (3)$$

If point Q is considered in the waterplane of the vessel, then the relative motion between it and the sea surface can be written as:

$$h = Z_0 - \theta X - \eta e^{i\omega t} \qquad (4)$$

Whenever $h > E\cos\theta$, the blades will be immersed. Consequently, if the relative motion between Q and the sea surface is known, Eq. (2) can be used to compute the probability of occurrence of blade tip immersions.

$$P_i = \exp(-E^2/\bar{h}^2) \qquad (5)$$

The number of immersions per hour can be computed as follows[2]:

$$N_{\mathrm{IPH}} = \frac{P_i}{2\pi}\sqrt{\frac{\mathrm{RMS}^2_{\dot{r}v}}{\mathrm{RMS}^2_{rm}}}\,3600 \qquad (6)$$

A tabulation of the results of Eq. (6) giving the immersions per hour of specified points on a helicopter is given in Table 2. In this case in all headings except the beam sea condition, the helicopter blade tips strike the sea surface quite often and risk damage. This indicates that the pilot should head along the direction of wave crests while the rotors are still turning. Normal pilot technique is to land into the wind which usually will mean landing into waves. The pilot will retain pitch attitude control through his normal flight control system and can maneuver as necessary to prevent rotor blade immersion. He can also control aircraft heading so as to orient the aircraft in the most advantageous position before engine and rotor shutdown.

Stability

General

Once a helicopter is waterborne, its overturning stability in both intact and damaged conditions becomes a pertinent consideration. A measure of this stability for boats and ships has been the maximum beam wind a vessel can endure without overturning, regardless of the loading condition. Crowding of passengers to one side and topside icing are also potential critical considerations. A helicopter, however, will not fly under heavy icing conditions.

Helicopters operate in a large variety of loading conditions. For example, the number and location of passengers, amount of fuel, and the amount and location of cargo are all variables which will significantly affect the loading of the helicopter.

Herein, procedures and criteria developed for boats and ships are used to evaluate the stability of the helicopter. The criteria are based on righting-heeling moment analyses with the following as the most important considerations: 1) available energy for righting vs heeling energy, 2) angular range of righting moment, and 3) angular location of maximum righting moment. Determining which loading conditions result in the smallest maximum righting arm and smallest range of positive righting arm can be done analytically by use of the Ship Hull Characteristics Program (SHCP).[6] Figure 2 shows a comparison of an SHCP righting-arm curve and an experimentally determined curve using a model with blades. The differences between the two may be due to the absence of blades from the theoretical result.

Table 2 Immersions per hour of specified points on a twin-rotor helicopter for five heading angles

Specified points	Heading angle, deg 0	45	90	135	180
1) Forward rotor tip, forward	169.6	26.9	0	96.4	251.6
2) Forward rotor	0	0	0.03	0.24	0
3) Aft rotor tip, aft	0.07	0	0	0	0.085
4) Aft rotor tip, to beam	0	0	0	0	0
5) Forward hatch	0	0	0	0	0

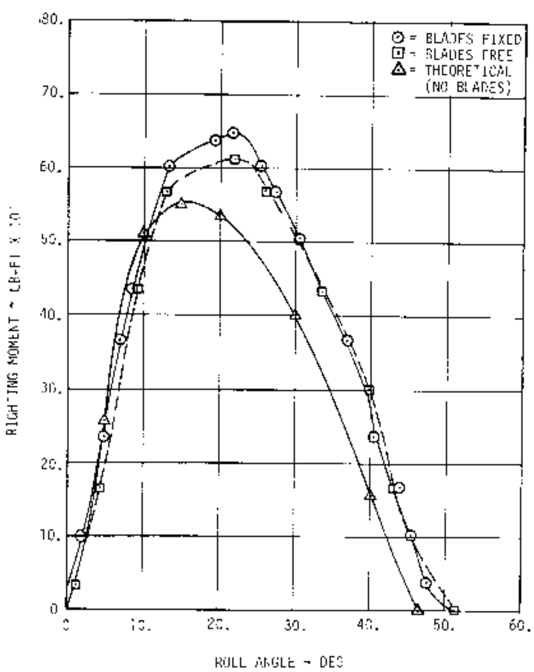


Fig. 2 Variation of righting moment with roll angle.

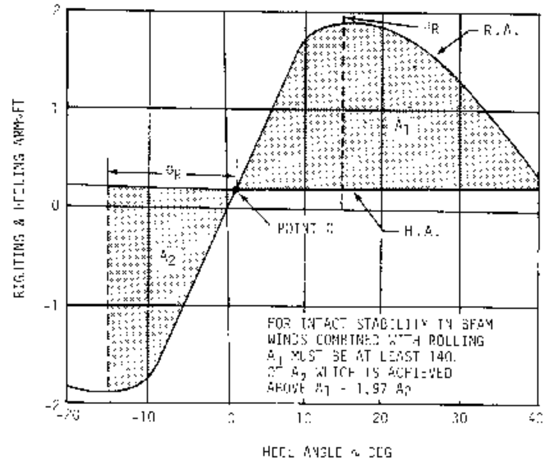


Fig. 3 Rolling motion stability analysis.

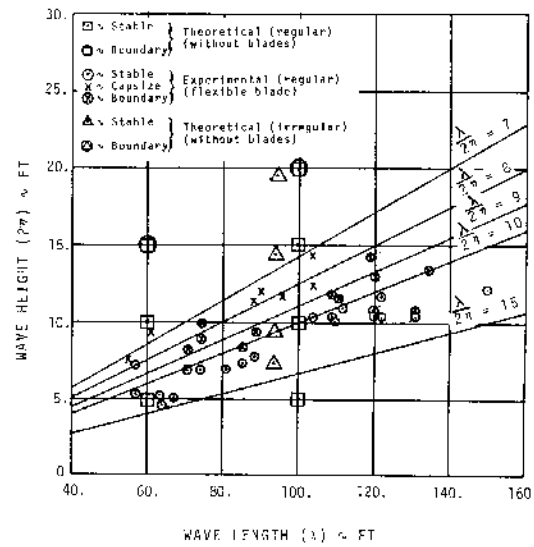


Fig. 4 Stability when floating in regular and irregular waves.

Intact Stability

The U.S. Navy,[7] American Bureau of Shipping,[8] U.S. Coast Guard,[9] and International Maritime Consulting Organization,[10] requirements and recommendations have a common criterion which can be applied to determine the maximum beam wind speed the helicopter can withstand. This criterion requires a ratio of 1.4 for the area under the righting-moment curve to the area under the heeling-moment curve, until the second point of intersection or the point of down flooding, whichever gives the least heel angle. By determining the projected area of the exposed portion of the helicopter including rotors, at increments of heel, wind heeling-arm curves can be generated for increments of wind speeds.

Damaged Stability

It is of interest to examine the stability of a helicopter for various damaged conditions because most of these vehicles have little or no watertight compartmentation within the fuselage. With the thin shell plating which must be used to construct the aircraft, in general there is a higher probability of shell puncture than for marine craft.

For a measure of the damaged stability, a reserve buoyancy criteria,[8] which requires a vessel to withstand a wind heeling moment superimposed from any direction can be used to find a maximum allowable wind speed. The wind heeling-arm curves used in the intact stability analysis can be used for the damaged stability with reasonable accuracy. The wind heeling-arm curve which intersects the maximum righting arm for the damaged condition in question yields the maximum allowable wind speed.

Correlation Between the Motion and Intact Stability Results

The analyses previously discussed do not explicitly address the interplay between motions and stability; however, the U.S. Navy does have a procedure for advanced vehicles which does this.[7]

Figure 3 shows an application of some of the principles of the Navy procedure. Although the intent of the latter is to assure stability under a predetermined extreme condition, herein the righting-heeling energy criteria were used to obtain a maximum allowable wind speed for a given sea state. Although the maximum roll motion θ_R is usually determined from model tests, herein the $A^{1/1000}$ amplitude short-term analytical roll response was used as the maximum. The area A_2 represents the energy imparted by wind and wave and must be absorbed in the opposite side roll (see Fig. 3). The area $(A_1 - A_2)$ represents a safety margin.

Figure 4 shows a comparison between model test and analytical capsizing results, both with no wind superimposed. The experimental boundary points are based on judgment during observation, while the analytical points are determined by a righting angle corresponding to 80% of the area under the righting-arm curve.

It is interesting to note that the experimental results indicate less resistance to capsizing even though the righting moment was determined to be greater for the experimental model than the analytical model (see Fig. 2). However, observations during the tests indicated that as wave height increased, it was a breaking wave with its attendant wave slap on the fuselage

Table 3 Summary of impact load procedures

Ref.	Method	Sea surface condition impact	Rigidity of impact surface	Two- or three-dimensional	Deadrise of impact surface	Factor of safety	Forward speed range	Aerodynamic lift
11	Theoretical	Smooth water, no waves	Rigid body	3D	Elliptical cross section	None	Variable	Equal to vehicle weight
12	Theoretical	Smooth water	Rigid body	2D corrected for 3D	Any	None	Variable	Equal to vehicle weight
13	Semiempirical	Smooth water	Rigid body	2D	Any	None	Variable	None
14	Semiempirical	Waves (deep-water trochoidal waves)	Rigid body	Mixture	Any	None	Variable	None
15	Naval architecture	Waves	Limited elasticity[a]	3D (empirical)	Any	Suggest use 1.5	Variable	None
17	Naval architecture	Rough seas	Limited elasticity	3D	Considered[a]	None	Any	None
18	Experiment	Smooth water	Rigid body	2D and 3D	Up to 15 deg	None	Zero speed	None
19	Experiment	Regular and irregular waves	Rigid body	2D and 3D	Considered[a]	None	Low	None

[a] Inherently considered in the experimental data.

which would capsize the helicopter. The analysis being based on linear seakeeping theory does not consider such a phenomenon, but it can be expected that waves with height greater than 1/10th length may break. Hence the results of analytical study may not be applicable above that boundary noted on Fig. 4.

Other reasons for the difference between analytical and experimental results could be the possible difference in the model vs full-scale wheel effects and the inclusion of flexible blades in the model tests. The affects of the latter are the introduction of time-varying forces as the blades thrash the sea surface.

Another aspect worthy of mention is that both the analytical studies and model test did not include the aerodynamic lift and control which would be generated if the helicopter were to remain under power. Experience has shown that under such a condition the seakeeping motions are significantly reduced.

Impact Loads

General

This section describes some of the methods available for predicting the seaway impact pressures of surface ocean vehicles. The purpose is to identify the best procedures for use in a hull structural analysis of a helicopter when impacting and planing on water during ditching.

As a result of a literature survey it was found that a great number of impact load studies for aircraft and surface vehicles have been performed, although few have been for helicopters. These present theories for the prediction of impact loads by means of model test results, theoretical approaches, empirical formulas, or combinations of the three. Most of the use of these methods has been in the design of marine vehicles. Herein, those methods which can be applied to a typical helicopter hull structure and which are considered to yield the most accurate impact loads are briefly reviewed for their historical and technical aspects. The detailed theoretical foundations of each method are not scrutinized. The major intent is to identify those procedures which seem to offer a potentially viable procedure for the initial hull-water impact and planing analyses of a helicopter.

The procedures are grouped into four major categories: theoretical, semiempirical, naval architectural, and experimental. Every reference has been reviewed within its category, with the following characteristics as prime considerations, so that a comparison and evaluation may be made on a common basis:

1) Sea surface condition at impact.
2) Rigidity of impact surface.
3) Two- or three-dimensional.
4) Deadrise of impact surface.
5) Factors of safety on load for structural design.
6) Speed range.
7) Aerodynamic lift considerations.

Actual numerical analyses for a helicopter were not performed with each of the methods, although this would be desirable for comparison purposes. No conclusions can be offered herein as to which procedure is considered the most applicable. A summary of the procedures is given in Table 3. It should be noted that some helicopters have fuselages with either flat or nearly flat bottoms. This aspect makes them fundamentally different from seaplanes for which more testing has been done.

Theoretical Procedures

Schnitzer and Hathaway[11] give an approximate method for computing water loads and pressure distributions on lightly loaded elliptical cylinders simulating helicopters during oblique smooth water impacts. It makes use of theory developed for landing impacts of seaplanes having cross sections of "V" and scalloped contours. The method addresses rigid hulls subjected to smooth water impact with aerodynamic lift equal to the vehicle weight. There is no independent full-scale experimental data available for verification of the procedures; however, a limited number of model experiments were conducted by dropping a circular semicylinder, 10 in. diameter by 3 ft length at 0 deg angle of trim, on a smooth surface at a vertical speed of 8.5 ft/s and zero forward speed. The experimental results reveal that there is a good agreement in transverse pressure distribution and that the predicted maximum impact pressure is about 20% less than that of experimental results.

Schnitzer[12] gives an analytical approach, based on a two-dimensional theory modified by a correction factor for three dimensions. He reports that the procedure can, with reasonable accuracy, predict the hydrodynamic loads and motions on a chine-immersed prismatic body.

A limited number of experiments were conducted in which a model was towed at constant forward speed with vertical and horizontal freedom. The comparison of the theoretical values with the experimental data reveals that fair agreement exists in most cases.

Semiempirical Procedures

Smiley[13] gives a procedure which is concerned only with the longitudinal and transverse water pressure distributions on flat and V-bottom prismatic surfaces during planing or impact. Both chine immersion and no chine immersion are considered. Smiley feels that the results for flat plates are good for trim angles less than 30 deg and for wetted length-to-beam ratios up to at least 3.3. The comparison of experimental data on the longitudinal distribution of pressure on a rectangular flat plate with predicted results shows that a good agreement exists.

Jones and Allen[14] present a semiempirical, quasistatic computerized method for calculating instantaneous three-dimensional water pressure distributions on high-speed marine vehicles. The method can simulate either planing or impact. The method can be used to obtain results of varying complexity, including a description of normal pressures for all or selected portions of the hull, a normalized pressure vs impact area relationship, and horizontal and vertical impact forces.

Naval Architectural Procedures

Owens Corning and Gibbs and Cox[15] give a simplified empirical relationship for maximum local pressure based on the results of Heller and Jasper.[16] It is claimed therein that the relationship is practical and conservative for determining bottom pressures on high-speed planing boats. It takes into account the effects resulting from the relative velocity of the water perpendicular to the hull bottom and orbital velocity of the water particles in the wave, and relates these values to the forward speed and size of the boat. This relationship includes coefficients determined from a single experiment conducted on an aluminum hull YP-110 (except PT-8)[16] at speeds of 28-35 knots in 5-6 ft waves. Also presented are longitudinal and transverse distributions of the maximum impact pressure as determined from the same experiment. Since the YP-110 hull surface was elastic, it is implied that any relationship based on its response considers that flexibility.

Jones and Allen[17] give designer-oriented empirical formulas that can be used to determine design pressures for high-performance marine vehicles such as ACVs, SESs, SWATHs, planing hulls, and hydrofoils. Curves for approximating the longitudinal pressure distribution are also given for the various vehicles.

The input required in this method that is the most difficult to obtain is the impact-load factor, or vertical acceleration at the c.g., N_Z. Load factors for a variety of high-performance vehicles are suggested. They have been developed based on a number of sea trials and are intended to be representative of the worst weather possible. External vehicle lift is not explicitly considered but it would seem that it could be by proper adjustment of the acceleration or impact-load factor.

Experimental

Chuang and Milne[18] give the results of a number of rigid-body drop tests that were performed with the objective of investigating the three-dimensional effects of slamming by comparing them to two-dimensional results. The three-dimensional models were a circular flat plate and five cone-shaped models with varying deadrise angles up to 15 deg. The two-dimensional models were wedges also with deadrise angles of 0-15 deg.

The tests reveal that the cone and wedge shapes with 0 and 1 deg angles of deadrise trap a considerable amount of air and push some of it into the surface layer of water, which tends to decrease the maximum pressure by providing a cushion. The tests also reveal that the maximum impact pressure is generally higher for the two-dimensional models.

SNAME[19] gives the results of a series of experiments in regular and irregular waves which were conducted on a barge model at even keel to investigate slamming of barges under tow. The bottom of the model had varying degrees of deadrise up to station 4. The area aft of station 5 was flat. The experiments were conducted at speeds of 1.13, 1.48, and 1.84 knots with the model free to heave, pitch, and surge but restricted in yaw, roll, and sway. The maximum impact pressure was found in the flat bottom area. The experimental results are represented by curves which also reveal that the two-dimensional impact pressures are higher than the three-dimensional, and the latter in waves are less than in calm water.

Conclusions

It appears that existing naval architectural methods for analyzing motions and stability can be applied on the analysis of waterborne helicopters. An example application has shown that experimental and analytical results do not agree particularly well, but not enough is known of either for a conclusive judgment.

There are few impact load prediction methods or tests that deal specifically with helicopters. A number of procedures and test data for predicting impact loads on high-performance craft should be applicable but need to be compared to each other and model tests for a conclusive judgment. The model tests should consider typical helicopter hull forms, aerodynamic lift, and structure.

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