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Aerodynamics Technical Memorandum 405

A MATHEMATICAL MODEL OF THE ON-DECK
HELICOPTER/SHIP DYNAMIC INTERFACE (U)

by

J. Blackwell and R.A. Feik

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Aerodynamics Technical Memorandum 405

A MATHEMATICAL MODEL OF THE ON-DECK
HELICOPTER/SHIP DYNAMIC INTERFACE

by

J. BLACKWELL and R.A. FEIK

SUMMARY

A mathematical model of the on-deck helicopter/ship dynamic interface has been developed and implemented on an ELXSI 6400 computer. The purpose of this work is to provide a capability for investigating helicopter/ship dynamic interactions, such as deck clearances on landing, swaying, toppling and sliding criteria, and tie-down loads. Different helicopter types can be readily examined, given their undercarriage representation. The model takes account of arbitrary ship motion, and includes features such as brakes on or off, tyre deformation and tyre sliding.



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CONTENTS

	Page No.
NOTATION	ii
1. INTRODUCTION	1
2. OUTLINE OF PROBLEM	1
3. FORCES ACTING ON HELICOPTER	2
3.1 Weight	2
3.2 Undercarriage	3
3.2.1 Oleo and Tyre Loads in z_b Direction	3
3.2.2 Side and Fore/Aft Tyre Forces	4
(I) Brakes Full On	4
(II) Brakes Off	6
4. MOMENTS ACTING ON HELICOPTER	6
4.1 Weight	7
4.2 Undercarriage	7
5. EXPRESSIONS FOR LINEAR AND ANGULAR ACCELERATION	7
5.1 Linear Acceleration	7
5.2 Angular Acceleration	8
6. APPLICATIONS	9
7. CONCLUDING REMARKS	11
ACKNOWLEDGEMENT	11
REFERENCES	12
APPENDIX A	13
FIGURES	

NOTATION

a	Acceleration of ship
C_x, C_y	Tyre spring coefficients in drag, slide directions
C_1, C_2, C_3	Constants used in C_x and C_y (dependent on tyre properties)
C_z	Tyre spring constant (z_b direction)
d	Oleo Deflection
d_o	Oleo Break Point
d'	Tyre compression (z_n direction)
F	Force acting on helicopter - subscripts <i>tot</i> (total), <i>g</i> (gravity), <i>u</i> (undercarriage), <i>t</i> (thrust), <i>aer</i> (aerodynamic), <i>r</i> (restraining devices)
F_s, F_b etc.	Frames of reference
F_u^*	Undercarriage force without sliding or dragging included
g	Acceleration due to gravity
$\mathbf{g}$	Gravity vector
G	Moment about helicopter cg. Subscripts as for F
G_1, G_2	Damping constants for oleo
G_x, G_y, G_z	Damping constants for tyre
h	Angular momentum of helicopter about its cg
$\tilde{I}$	Matrix determined from moments of Inertia for helicopter
I_x, I_y, I_z	Moments of inertia for helicopter
I_{xy}, I_{xz}, I_{yz}	Moment of inertia crossed terms for helicopter
$\tilde{J}^{rel}$	Matrix required for conversion from ω_b^{rel} to $\dot{\theta}^{rel}$
K_1, K_2	Spring constants for oleo
L	Oleo load, magnitude, L_1
$\tilde{L}_{bs}$	Change of reference frame matrix from frame <i>s</i> to <i>b</i> (Appendix A)
L_x, L_y, L_z	Gear moment arms (location of top of oleos relative to helicopter cg, in <i>x</i> , <i>y</i> and <i>z</i> directions)
L_1, L_2	Magnitude of oleo load, tyre load
M	Mass of helicopter
$\mathbf{r}$	Position vector from ship cg to helicopter cg
$\mathbf{r}'$	Position vector from helicopter cg to tyre contact point with deck
R	Reaction force of tyre (normal to deck)
$\Delta x_a, \Delta y_a$	Tyre deformation in fore/aft, side directions

$\dot{\Delta y}_a, \dot{\Delta y}_s$	Rate of tyre deformation in fore/aft, side directions
ϕ^b, θ^b, ψ^b	Helicopter attitude (Euler angles from earth frame to helicopter frame); roll, pitch, yaw
$\phi^{rel}, \theta^{rel}, \psi^{rel}$	Relative attitude (Euler angles from ship frame to helicopter frame); roll, pitch, yaw
ϕ^s, θ^s, ψ^s	Ship attitude (Euler angles from earth frame to ship frame); roll, pitch, yaw
μ_x, μ_y	Drag and slide tyre friction coefficients
ω^b	Absolute angular velocity of helicopter (relative to earth)
ω^{rel}	Angular velocity of helicopter relative to ship
ω^s	Absolute angular velocity of ship (relative to earth)

SUBSCRIPTS (AXES SYSTEM)

a	Aligned axes system
b	Body (helicopter) axes system
e	earth axes system (assumed inertial)
s	ship axes system

SUPERSCRIPTS

j	refers to j th undercarriage gear, eg. F_u^j is undercarriage force due to j th gear
---	--

GENERAL

Vectors written in bold type, eg. $\mathbf{r}$

Matrices distinguished by a *tilda*, eg. $\tilde{L}$

1. INTRODUCTION

The current use of helicopters with non aviation ships creates many difficulties, especially during landing in the presence of high winds and rough seas (Ref. 1). Some of these problems are being partially addressed by the development of devices such as the "Landing Period Designator" (Ref. 2), which attempts to predict relatively quiescent deck motion intervals. However, once the helicopter is on the deck, new problems arise. The deck motion now acts directly on the helicopter landing gear and may cause the helicopter to oscillate or slide, making deck operations hazardous. In high sea states, the helicopter may even topple, causing possible damage and putting deck personnel at risk.

The Aircraft Behaviour Studies - Rotary Wing (ABS-RW) Group at Aeronautical Research Laboratory (ARL) is currently engaged in a project to examine the on-deck aspect of the helicopter/ship dynamic interface problem. This document describes a mathematical model which simulates helicopter interactions with a moving deck. Rotor thrust and other aerodynamic forces are not included in the model at this stage. However their inclusion is relatively straightforward, and will be implemented during the validation stage.

Section 2 briefly outlines the problem and discusses the various frames of reference utilised. Sections 3 and 4 examine the forces and moments which act on the helicopter while on an arbitrarily moving deck. These comprise mainly the undercarriage forces, which are modelled using non-linear equations. Features such as brakes on or off, tyre deformation and tyre sliding are included in the model. In Section 5, the linear and angular accelerations are deduced. Section 6 uses the mathematical model to predict helicopter motions under a variety of deck conditions. Section 7 concludes the document, whilst Appendix A outlines the unsteady equations required by the model.

The model, which is not specific to a particular helicopter, was implemented on an *ELXSI/6400* computer. A standard *FORTTRAN* version, as well as a simulation language version (*ACSL*, Ref. 3) was written.

2. OUTLINE OF PROBLEM

Consider a helicopter resting on a ship. Forces acting on the helicopter (eg. gravity, undercarriage) can be analysed in terms of forces on the helicopter cg and moments about the cg. These forces and moments create both linear and angular accelerations of the helicopter relative to the ship. The accelerations can be integrated numerically to determine position and attitude of the helicopter relative to the ship as a function of time, for various ship motions. Note that we are calculating the position and attitude of a moving reference frame (helicopter) relative to a different moving reference frame (ship), see Fig. 1, and hence the full unsteady equations of motion are required (see eg. Ref. 4). Those unsteady equations required by the model are summarised in Appendix A.

The axes systems used here are earth, body (helicopter) and ship. They are represented by subscripts e, b and s respectively (Fig 2). A further axes system, represented by subscript a, is introduced in Section 3.

3. FORCES ACTING ON HELICOPTER

The forces acting on the helicopter are :

- Weight (gravity)
- Undercarriage
- Rotor Thrust
- Aerodynamic Forces
- Restraining Devices

The net force, F_{tot} is the sum of the above forces :

$$F_{tot} = F_g + F_u + F_r + F_{aer} + F_r \quad [1]$$

We consider here only the weight and undercarriage terms.

3.1 Weight

Gravity acts vertically downwards in earth axes :

$$g_e = \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} \quad [2]$$

Converting to ship axes (see Appendix A), we obtain :

$$g_s = \tilde{L}_{se} g_e \quad [3]$$

where :

$$\tilde{L}_{se} = \begin{pmatrix} \cos\theta^s \cos\psi^s & \cos\theta^s \sin\psi^s & -\sin\theta^s \\ \sin\phi^s \sin\theta^s \cos\psi^s - \cos\phi^s \sin\psi^s & \sin\phi^s \sin\theta^s \sin\psi^s + \cos\phi^s \cos\psi^s & \sin\phi^s \cos\theta^s \\ \cos\phi^s \sin\theta^s \cos\psi^s + \sin\phi^s \sin\psi^s & \cos\phi^s \sin\theta^s \sin\psi^s - \sin\phi^s \cos\psi^s & \cos\theta^s \cos\phi^s \end{pmatrix}$$

with superscript s referring to the Euler angles of the ship frame relative to the earth frame.

The force due to gravity, F_g is given by :

$$F_{gs} = Mg_s = Mg \begin{pmatrix} -\sin\theta^s \\ \cos\theta^s \sin\phi^s \\ \cos\theta^s \cos\phi^s \end{pmatrix} \quad [4]$$

3.2 Undercarriage

For each gear, consider the model shown in Fig. 3.

3.2.1 Oleo and Tyre Loads In z_b Direction

The oleos are assumed to compress parallel to the body z -axis, a condition that can be relaxed relatively easily. Each oleo is represented as a two-stage non-linear damped spring with a break point (described in Ref. 5). The oleo load, L_1 is given by :

$$L_1 = \begin{cases} K_1 d^2 + G_1 \dot{d} & (\text{for } d < d_o) \\ K_1 d_o^2 + K_2(d-d_o)^2 + G_2 \dot{d} & (\text{for } d \geq d_o) \end{cases}$$

where d is the oleo deflection. The tyre on the end of each oleo will also deform under a z_b load. Each tyre (z_b direction) is represented by a linear, damped spring, with load, L_2 given by :

$$L_2 = C_z \dot{d} + G_z d \quad [5]$$

where d is the tyre compression in the z_b direction. $L_1 = L_2$ since the tyre is assumed to be a massless spring. See Fig. 4.

The oleo load due to the j th gear, L^j in body axes is given by :

$$L_b^j = \begin{pmatrix} 0 \\ 0 \\ -L_1^j \end{pmatrix} \quad [6]$$

In ship axes, the oleo load is :

$$L_s^j = \tilde{L}_{sb} L_b^j \quad [7]$$

where :

$$\tilde{L}_{sb} = \begin{pmatrix} \cos\theta^{rel}\cos\psi^{rel} & \sin\phi^{rel}\sin\theta^{rel}\cos\psi^{rel} - \cos\phi^{rel}\sin\psi^{rel} & \cos\phi^{rel}\sin\theta^{rel}\cos\psi^{rel} + \sin\phi^{rel}\sin\psi^{rel} \\ \cos\theta^{rel}\sin\psi^{rel} & \sin\phi^{rel}\sin\theta^{rel}\sin\psi^{rel} + \cos\psi^{rel}\cos\phi^{rel} & \cos\phi^{rel}\sin\theta^{rel}\sin\psi^{rel} - \sin\phi^{rel}\cos\psi^{rel} \\ -\sin\theta^{rel} & \sin\phi^{rel}\cos\theta^{rel} & \cos\theta^{rel}\cos\phi^{rel} \end{pmatrix}$$

with superscript *rel* referring to the Euler angles of the helicopter frame relative to the ship frame.

Hence :

$$L_s^j = -L_1^j \begin{pmatrix} \cos\phi^{rel}\sin\theta^{rel}\cos\psi^{rel} + \sin\phi^{rel}\sin\psi^{rel} \\ \cos\phi^{rel}\sin\theta^{rel}\sin\psi^{rel} - \sin\phi^{rel}\cos\psi^{rel} \\ \cos\theta^{rel}\cos\phi^{rel} \end{pmatrix} \quad [8]$$

3.2.2 Side and Fore/Aft Tyre Forces

All the undercarriage wheels are assumed to point in the direction of the body x-axis at this stage, i.e. no provision has been made for a castoring tail wheel. The brakes on each wheel can be either full on (wheel locked) or off (wheel can rotate freely).

i) Brakes Full On

If a tyre is in contact with the deck ($L_1 > 0$), any movement of the oleo base (wheel axle) parallel to the plane of the deck will be opposed by a friction force at the point of contact between the tyre and the deck, which will deform the tyre and create a restoring force. When the maximum static friction force is exceeded, the wheel will skid over the deck.

It is necessary to define a new reference frame, the a-frame (a for *aligned*), obtained by simply rotating the ship-axes frame about the z_s axis through angle ψ^{rel} . This takes account of the ship and helicopter not being aligned and is required because whilst any skidding of the helicopter clearly takes place in the plane of the deck (x_s - y_s plane), restoring forces are likely to differ for *sliding* (skidding in the direction of the component of y_b in the x_s - y_s plane, the *side* direction, y_a), and *dragging* (skidding in the direction of the component of x_b in the x_s - y_s plane, the *fore/aft* direction, x_a). See Fig. 5. The representation of these restoring forces for the *side* and *fore/aft* directions is a function of tyre geometry.

The L-matrix from frame s to frame a is :

$$\tilde{L}_{as} = \begin{pmatrix} \cos\psi^{rel} & \sin\psi^{rel} & 0 \\ -\sin\psi^{rel} & \cos\psi^{rel} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad [9]$$

Given the updated position and attitude of the helicopter during a time history calculation, it is possible to determine the position of each oleo. Assuming that the tyre base is at its original (i.e. previous iteration) position, the possible tyre deformation in the plane of the deck, $(\Delta x_s, \Delta y_s)$ is deduced and hence $(\Delta x_a, \Delta y_a) = (\cos\psi^{rel}\Delta x_s + \sin\psi^{rel}\Delta y_s, \cos\psi^{rel}\Delta y_s - \sin\psi^{rel}\Delta x_s)$ is obtained (Fig. 6). If however the tyre should leave the deck, the deformation is set equal to zero.

Restoring forces in the x_a and y_a directions are assumed to be directly proportional to tyre deformations Δx_a and Δy_a respectively (Ref. 6), and are given by $(-C_x \Delta x_a, -C_y \Delta y_a)$. The spring coefficients C_x and C_y are not taken as constant, but are assumed to vary with vertical tyre deflection, d , according to the approximate relation (Loc. Cit.) :

$$C_x \approx C_1 \sqrt[3]{d} \quad [10]$$

$$C_y \approx C_2 - C_3 d \quad [11]$$

for constants C_1 , C_2 and C_3 which depend on the tyre properties.

The damping in the x_a and y_a directions is assumed to be directly proportional to the *rate* of tyre deformation in the respective directions, $\dot{\Delta x}_a$ and $\dot{\Delta y}_a$.

The total undercarriage forces in the side and fore/aft directions may also contain a component of the oleo load, L_1^j if the oleo is not perpendicular to the deck. From equations [8] and [9], the j^{th} oleo load in the a-frame, L_a^j is given by :

$$L_a^j = \tilde{L}_{as} L_s^j = \begin{pmatrix} -\cos\phi^{\text{rel}}\sin\theta^{\text{rel}} \\ \sin\phi^{\text{rel}} \\ -\cos\phi^{\text{rel}}\cos\theta^{\text{rel}} \end{pmatrix} L_1^j \quad [12]$$

Thus, the total force acting on the j^{th} gear (in a-axes), assuming deck contact and assuming no sliding or dragging, is :

$$F_{u_a}^j = \begin{pmatrix} -C_x^j \Delta x_a^j - G_x^j \dot{\Delta x}_a^j - \cos\phi^{\text{rel}}\sin\theta^{\text{rel}} L_1^j \\ -C_y^j \Delta y_a^j - G_y^j \dot{\Delta y}_a^j + \sin\phi^{\text{rel}} L_1^j \\ -\cos\phi^{\text{rel}}\cos\theta^{\text{rel}} L_1^j \end{pmatrix} \begin{matrix} \leftarrow \text{total force in fore/aft direction} \\ \leftarrow \text{total force in side direction} \\ \leftarrow \text{total force normal to deck} \end{matrix} \quad [13]$$

If the j^{th} tyre is off the deck, $F_{u_a}^j$ is clearly zero. The forces for a sliding or dragging tyre are discussed next.

The limiting friction forces in the fore/aft and side directions are $\mu_x^j R^j$ and $\mu_y^j R^j$ respectively. R^j , the force normal to the deck, is given by the modulus of $F_{u_a}^j$ (Equation 13), and is equal to $\cos\phi^{\text{rel}}\cos\theta^{\text{rel}} L_1^j$. If the modulus of the fore/aft force (or side force) in equation [13] exceeds the limiting drag (slide) friction, then the fore/aft (side) force is set equal to the limiting friction and the tyre base is moved rigidly with the oleo, such that the deformation (in the plane of the deck) of the previous iteration is retained. Thus, no new tyre deformation (in the plane of the deck) is assumed to occur and the tyre drags (slides). If the fore/aft (side) force does not exceed the limiting value, the tyre base is not moved and instead the tyre deforms. See Fig. 7.

Final equations for the j^{th} gear load, $F_{u_a}^j$ are :

$$F_{u_a}^j = \begin{pmatrix} F_{u_a}^j|_x \\ F_{u_a}^j|_y \\ -R^j \end{pmatrix} \quad [14]$$

where :

$$R^j = \cos\phi^{\text{rel}}\cos\theta^{\text{rel}} L_1^j \quad [15]$$

$$F_{u_a}^j|_x = \begin{cases} F_{u_a}^j|_x & |F_{u_a}^j|_x| \leq \mu_x^j R^j & (\text{tyre doesn't drag}) \\ \mu_x^j R^j \cdot \text{sign}(F_{u_a}^j|_x) & |F_{u_a}^j|_x| > \mu_x^j R^j & (\text{tyre drags}) \end{cases} \quad [16]$$

$$F_{u_a}^j|_y = \begin{cases} F_{u_a}^j|_y & |F_{u_a}^j|_y| \leq \mu_y^j R^j \quad (\text{tyre doesn't slide}) \\ \mu_y^j R^j \cdot \text{sign}(F_{u_a}^j|_y) & |F_{u_a}^j|_y| > \mu_y^j R^j \quad (\text{tyre slides}) \end{cases} \quad [17]$$

with :

$$F_{u_a}^j|_x = -C_x^j \Delta x_a^j - G_x^j \dot{\Delta x}_a^j - \cos\phi^{rel} \sin\theta^{rel} L_1^j \quad [18]$$

$$F_{u_a}^j|_y = -C_y^j \Delta y_a^j - G_y^j \dot{\Delta y}_a^j + \sin\phi^{rel} L_1^j \quad [19]$$

$$\text{sign}(F) = \frac{F}{|F|} \quad [20]$$

unless the j^{th} gear is off the ground, in which case $F_{u_a}^j = 0$.

ii) Brakes Off

For the case of brakes off, the undercarriage wheel (assuming frictionless bearings and neglecting rolling friction) can rotate freely in the x_a direction and so does not drag or deform. This affects the x_a forces as shown below. The sliding or deformation in the y_a direction is assumed to be unaffected by the status of the brakes, and so behaves as in the preceding section.

Given the updated position of the oleo, the tyre is assumed to move in the x_a direction such that it is in line with the oleo, i.e. no deformation takes place, and hence no restoring force acts in the x_a direction. Thus, the x_a component of $F_{u_a}^j$ contains only the x_a component of oleo load and is modified from equation [16] to read :

$$F_{u_a}^j|_x = -\cos\phi^{rel} \sin\theta^{rel} L_1^j \quad [21]$$

with y_a and z_a components assumed to be unaffected.

For brakes on or off, the oleo load L_1^j is determined from the oleo and tyre z_b deflections. These are obtained from the helicopter position and attitude, as are the tyre displacements in the plane of the deck, Δx_a^j and Δy_a^j . Summation of F_u^j over the separate gears leads to the resultant undercarriage force, F_u :

$$F_{u_s}^j = \tilde{L}_{sa} F_{u_a}^j \quad [22]$$

$$F_{u_s} = \sum_j F_{u_s}^j \quad [23]$$

4. MOMENTS ACTING ON HELICOPTER

The forces discussed in Section 3 do not in general act at the helicopter cg, and hence moments are created about the cg. The net moment about the cg, G_{tot} is defined as the sum of the moments due to the afore mentioned forces :

$$G_{tot} = G_g + G_u + G_t + G_{uor} + G_r \quad [24]$$

with only the weight and undercarriage terms considered here.

4.1 Weight

The moment due to gravity, G_g , is zero since gravity acts at the helicopter cg.

4.2 Undercarriage

The net force acting on the j th gear is given by F_u^j , equations [14] - [17]. The moment about the helicopter cg due to this force, G_u^j is :

$$G_{us}^j = F_{us}^j \times r_s^j \quad [25]$$

where r^j is the position vector from the helicopter cg to the j th tyre contact point with the deck (Fig. 8).

Summation of G_u^j over the separate gears leads to the resultant moment about the helicopter cg due to undercarriage forces, G_u :

$$G_{ub}^j = \tilde{L}_{bs} G_{us}^j \quad [26]$$

$$G_{ub} = \sum_j G_{ub}^j \quad [27]$$

Given the force acting on the helicopter cg and the moment tending to rotate the helicopter about its cg, the linear and angular accelerations can be determined. Numerical integration (fourth-order Runge-Kutta) is then used to deduce the position, attitude and velocity of the helicopter with respect to the ship.

5. EXPRESSIONS FOR LINEAR AND ANGULAR ACCELERATION

Not only is the position and attitude of the helicopter relative to the ship changing with time, but the ship's position and attitude relative to the earth is also constantly changing. Hence it is necessary to use the full unsteady equations of motion which take account of the moving reference frames.

5.1 Linear Acceleration

If r is the position vector of the helicopter cg relative to the ship cg (Fig. 9), then from Ref. 4 :

$$\ddot{r}_s = \frac{F_{tot_s}}{M} - a_s - \dot{\omega}_s^2 \times r_s - 2\omega_s \times \dot{r}_s - \omega_s^2 \times (\omega_s \times r_s) \quad [28]$$

where :

$\mathbf{a}$ = acceleration of ship cg (relative to earth)

ω^s = angular velocity of ship (relative to earth)

M = mass of helicopter

$\mathbf{F}_{tot}$ = total force acting on helicopter

Thus, given the net force acting on the helicopter cg in ship axes (calculated in Section 3), the ship's acceleration, angular velocity and angular acceleration relative to earth (input to model), and the current position and velocity of the helicopter cg relative to the ship (deduced by numerical integration over the previous time step), we can calculate the acceleration of the helicopter relative to the ship, $\ddot{\mathbf{r}}_s$. Numerical integration is then used to determine updated values for the velocity and position of the helicopter, $\dot{\mathbf{r}}_s$ and $\mathbf{r}_s$.

5.2 Angular Acceleration

If ω^b is the absolute angular velocity of the helicopter (relative to earth), and $\mathbf{G}_{tot}$ is the net moment about the helicopter cg, calculated in Section 4, then the angular acceleration of the helicopter, $\dot{\omega}^b$ is given by (see Appendix A) :

$$\dot{\omega}^b = \tilde{\mathbf{I}}^{-1} [\mathbf{G}_{tot} - \omega^b \times (\tilde{\mathbf{I}} \omega^b)] \quad [29]$$

where $\tilde{\mathbf{I}}$ is obtained from the helicopter moments of inertia, and is given by :

$$\tilde{\mathbf{I}} = \begin{pmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{xy} & I_y & -I_{yz} \\ -I_{xz} & -I_{yz} & I_z \end{pmatrix} \quad [30]$$

Numerical integration is then used to determine an updated value for ω^b , which is used to deduce the angular velocity of the helicopter relative to the ship, ω^{rel} from the relation :

$$\omega^{rel} = \omega^b - \tilde{\mathbf{L}}_{bs} \omega_s^s \quad [31]$$

The Euler angle rates are developed in Ref. 4, and as shown in Appendix A are given by :

$$\begin{pmatrix} \dot{\phi}^{rel} \\ \dot{\theta}^{rel} \\ \dot{\psi}^{rel} \end{pmatrix} = \tilde{\mathbf{J}}^{rel} \omega^{rel} \quad [32]$$

numerical integration can now be used to determine ϕ^{rel} , θ^{rel} and ψ^{rel} , the attitude of the helicopter relative to the ship.

Given updated values of relative position and attitude, the whole procedure is now repeated.

6. APPLICATIONS

Consider a helicopter "dropped" from a horizontal position, onto a ship deck which has a variety of attitudes and motions. For the purpose of illustration, we restrict ourselves to $\psi^{rel} = 0^\circ$ (helicopter and ship aligned), and the ship is allowed to deviate from the horizontal position in roll only (Fig. 10). The helicopter considered has two main landing gears with brakes *ON*, and a single tail gear without brakes (ie. tail brake taken as *OFF* in the mathematical model). Rotor thrust and other aerodynamic forces are taken as zero for this idealised case.

The following cases are considered :

- case 1 - deck horizontal and stationary
- case 2 - deck at 10° roll and stationary
- case 3 - deck rolling sinusoidally from -10° to $+10^\circ$ with period 10 seconds

The various parameters representing the helicopter are listed in Tables 1 and 2.

Table 1. Helicopter Parameters

Parameter	SI	Imperial
M	9.0×10^3 Kg	2.0×10^4 lb
I_x	9.0×10^3 Kg m ²	2.1×10^5 lb ft ²
I_y	6.3×10^4 Kg m ²	1.5×10^6 lb ft ²
I_z	6.0×10^4 Kg m ²	1.4×10^6 lb ft ²
$I_{xz}=I_{zx}$	2.5×10^3 Kg m ²	5.9×10^4 lb ft ²
$I_{xy}=I_{yx}$	0.0 Kg m ²	0.0 lb ft ²
$I_{yz}=I_{zy}$	0.0 Kg m ²	0.0 lb ft ²

The mathematical model developed earlier is used to predict the variation of oleo load and oleo deflection with time for the above three cases.

Case 1 - See Fig. 11. The oleo load and deflection variation for gears 1 and 2 are the same due to symmetry. The helicopter comes to rest in about three seconds, with greater compression of the tail wheel oleo than the main gear oleos.

Case 2 - See Fig. 12. Due to the initial horizontal attitude of the helicopter, the left main gear (1) makes contact with the deck first, followed by the tail gear (3) and finally the right main gear (2). After making deck contact, gear 1 actually leaves the deck for a short while. Case 2

takes longer to damp out than case 1, as expected, and the helicopter comes to rest after about six seconds, with the right main gear (2) more compressed than the left main gear (1).

Case 3 - See Fig. 13. The relatively gentle ship rolling motion has little effect on oleo load and deflection during the initial impact (compare Figs. 12 and 13), however by five seconds, when the ship deck is now inclined the other way, a reversal of the loads on the main gears has taken place. If the variation of oleo load and deflection is examined over a greater time span (Fig. 14), it is seen that a periodicity in the helicopter motion soon develops, with period 10 seconds equal to that of the ship. The helicopter is seen to oscillate between the two main gears, with the tail gear oleo load and deflection remaining virtually constant.

Table 2. Helicopter Landing Gear Parameters

Parameter	MAIN GEAR		TAIL GEAR	
K_1	$3.6 \times 10^5 \text{ Nm}^{-2}$	$(7.5 \times 10^3 \text{ lbf/ft}^2)$	$1.8 \times 10^5 \text{ Nm}^{-2}$	$(3.8 \times 10^3 \text{ lbf/ft}^2)$
K_2	$5.0 \times 10^6 \text{ Nm}^{-2}$	$(1.0 \times 10^5 \text{ lbf/ft}^2)$	$2.0 \times 10^6 \text{ Nm}^{-2}$	$(4.2 \times 10^4 \text{ lbf/ft}^2)$
G_1	$2.2 \times 10^4 \text{ Nsm}^{-1}$	$(1.5 \times 10^3 \text{ lbf s/ft})$	$1.8 \times 10^4 \text{ Nsm}^{-1}$	$(1.2 \times 10^3 \text{ lbf s/ft})$
G_2	$4.0 \times 10^4 \text{ Nsm}^{-1}$	$(2.7 \times 10^3 \text{ lbf s/ft})$	$3.0 \times 10^4 \text{ Nsm}^{-1}$	$(2.1 \times 10^3 \text{ lbf s/ft})$
d_0	0.238 m	(0.781 ft)	0.335 m	(1.099 ft)
C_2	$6.0 \times 10^5 \text{ Nm}^{-1}$	$(4.1 \times 10^4 \text{ lbf/ft})$	$8.0 \times 10^5 \text{ Nm}^{-1}$	$(5.5 \times 10^4 \text{ lbf/ft})$
C_1	$1.4 \times 10^6 \text{ Nm}^{-1.33}$	$(6.5 \times 10^4 \text{ lbf/ft}^{1.33})$	$8.0 \times 10^5 \text{ Nm}^{-1.33}$	$(3.9 \times 10^4 \text{ lbf/ft}^{1.33})$
C_2	$4.5 \times 10^5 \text{ Nm}^{-1}$	$(3.1 \times 10^4 \text{ lbf/ft})$	$6.0 \times 10^5 \text{ Nm}^{-1}$	$(4.1 \times 10^4 \text{ lbf/ft})$
C_3	$1.2 \times 10^6 \text{ Nm}^{-2}$	$(2.5 \times 10^4 \text{ lbf/ft}^2)$	$1.0 \times 10^6 \text{ Nm}^{-2}$	$(2.1 \times 10^4 \text{ lbf/ft}^2)$
G_x	$2.0 \times 10^4 \text{ Nsm}^{-1}$	$(1.4 \times 10^3 \text{ lbf s/ft})$	$2.0 \times 10^4 \text{ Nsm}^{-1}$	$(1.4 \times 10^3 \text{ lbf s/ft})$
G_y	$2.0 \times 10^4 \text{ Nsm}^{-1}$	$(1.4 \times 10^3 \text{ lbf s/ft})$	$2.0 \times 10^4 \text{ Nsm}^{-1}$	$(1.4 \times 10^3 \text{ lbf s/ft})$
G_z	$1.0 \times 10^4 \text{ Nsm}^{-1}$	(685 lbf s/ft)	$1.0 \times 10^4 \text{ Nsm}^{-1}$	(685 lbf s/ft)
L_x	1.5 m	(4.92 ft)	3.3 m	(10.83 ft)
L_y	1.4 m	(4.59 ft)	0.0 m	(0.0 ft)
L_z	0.8 m	(2.62 ft)	0.6 m	(1.97 ft)
μ_x	0.7	(0.7)	0.7	(0.7)
μ_y	0.7	(0.7)	0.7	(0.7)

A possible further application of the model is to examine the varying distance between the ship deck and a part of the helicopter. For instance, the Sikorsky SH-60B Sea Hawk has a radome located under its chin which could possibly come close to the deck during a heavy landing, or while the helicopter is on the deck during rough seas. In Fig. 15, the distance between the deck and a hypothetical radome (location [2.5, 0, 1.5]m relative to the helicopter

cg), is plotted for the conditions of case 3. More realistic situations would require the use of measured ship motions as forcing inputs.

7. CONCLUDING REMARKS

A mathematical model has been described which models a helicopter on an arbitrarily moving deck. The model has been successfully implemented on an *ELXSI 6400* Computer. Results so far, for a deck at rest and oscillating sinusoidally, agree with expected trends. It is planned to validate the model using actual helicopter data in the near future.

The oleo load and deflection have been examined here, but other variables of interest, such as deck clearance of a portion of the helicopter, or clearances with nearby obstacles due to swaying, can be easily determined. The model can also be used for developing sliding and toppling criteria.

The addition of restraining devices (tie down and RAST¹ loads) is desired to extend the capabilities of the on-deck model. It is also intended to include rotor thrust and aerodynamic forces in the model, and a stability augmentation system (SAS), so that actual landings on an arbitrarily moving deck can be studied. Other assumptions, for example that oleo loads act in the direction of the body z-axis, can be relatively easily relaxed.

The model is readily adaptable to different helicopter types. In particular, the undercarriage representation can be varied, either by changing the parameters in the present model, or by providing an alternative representation, without changes being required in other parts of the model.

Finally, the model has been developed so as to facilitate the incorporation of either part or all of it into wider system studies of the helicopter/ship dynamic interface.

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¹ Recovery Assist Secure and Traverse system

REFERENCES

1. Healey, J.V. : Simulating the Helicopter/Ship Interface as an Alternative to Current Methods of Determining Safer Operating Envelopes. *A Preliminary Report to the Naval Air Systems Command*, Dec. 1985.
2. O'Reilly, P.J.F. : Aircraft/Deck Interface Dynamics for Destroyers. *Marine Technology*, 24 (1), 15-25, Jan. 1987.
3. Anon. : Advanced Continuous Simulation Language (ACSL) - User Guide / Reference Manual. *Mitchell & Gauthier Assoc., USA*, 1981.
4. Elkin, B. : Dynamics of Atmospheric Flight. *Wiley*, 1972.
5. Blackwell, J. : A Maximum Likelihood Parameter Estimation Program for General Non-Linear Systems. *ARL Aero. TM - 392*, January 1988.
6. Smiley, R. F. & Horne, W. B. : Mechanical Properties of Pneumatic Tires with Special Reference to Modern Aircraft Tyres. *NASA TR R-64*, 1960.

APPENDIX A

Unsteady Equations of Motion

Due to the non-steady nature of the on-deck problem, the unsteady equations of motion are required. For a full discussion of these equations, see eg. Ref.4. The main relationships used in this document are listed below, with the relevant section number from Ref. 4 listed in brackets where appropriate. The earth frame is assumed to be inertial throughout.

Position and Velocity Vectors in Different Reference frames

Consider two reference frames eg. b and s. If r_b is a vector viewed from frame b, and r_s is the same vector viewed from frame s, then r_b and r_s are related to one another as follows :

$$r_b = \tilde{L}_{bs} r_s \quad (\$4.4) \quad [A1]$$

where $\tilde{L}_{bs}$ is the change of reference frame matrix from s to b given by :

$$\tilde{L}_{bs} = \begin{pmatrix} \cos\theta^{rel}\cos\psi^{rel} & \cos\theta^{rel}\sin\psi^{rel} & -\sin\theta^{rel} \\ \sin\phi^{rel}\sin\theta^{rel}\cos\psi^{rel} - \cos\phi^{rel}\sin\psi^{rel} & \sin\phi^{rel}\sin\theta^{rel}\sin\psi^{rel} + \cos\psi^{rel}\cos\phi^{rel} & \sin\phi^{rel}\cos\theta^{rel} \\ \cos\phi^{rel}\sin\theta^{rel}\cos\psi^{rel} + \sin\phi^{rel}\sin\psi^{rel} & \cos\phi^{rel}\sin\theta^{rel}\sin\psi^{rel} - \sin\phi^{rel}\cos\psi^{rel} & \cos\theta^{rel}\cos\phi^{rel} \end{pmatrix}$$

and ϕ^{rel} , θ^{rel} and ψ^{rel} are the Euler angles that take frame s to frame b.

Note that :

$$\tilde{L}_{sb} = \tilde{L}_{bs}^T \quad (\$4.4) \quad [A2]$$

The rate of change of vector r when viewed from frame b, $\dot{r}_b$ is related to the rate of change of the same vector when viewed from frame s, $\dot{r}_s$ by :

$$\dot{r}_b = \tilde{L}_{bs} \dot{r}_s - \omega_b^{rel} \times r_b \quad (\$4.6) \quad [A3]$$

where ω_b^{rel} is the angular velocity of frame b relative to frame s.

Angular Rates in Different Reference frames

If G is the moment and h the associated angular momentum of a body about its cg, then in body axes, b :

$$G_b = \dot{h}_b + \omega_b^b \times h_b \quad (\$5.6) \quad [A4]$$

providing that the origin of the body axes is the body cg. ω_b^b is the absolute angular velocity of frame b (relative to earth).

For a rigid body, the angular momentum is given by .

$$h_b = \tilde{I} \omega_b^b \quad (\$5.4) \quad [A5]$$

where $\tilde{I}$ is obtained from the body (helicopter) moments of inertia :

$$\tilde{I} = \begin{pmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{xy} & I_y & -I_{yz} \\ -I_{xz} & -I_{yz} & I_z \end{pmatrix} \quad [A6]$$

and :

$$I_x = \int (y^2 + z^2) dm \quad \text{etc.} \quad [A7]$$

$$I_{xy} = \int xy dm \quad \text{etc.} \quad [A8]$$

Equations [A4] and [A5] result in :

$$G_b = \tilde{I} \dot{\omega}_b^b + \omega_b^b \times (\tilde{I} \omega_b^b) \quad (\$5.6) \quad [A9]$$

Finally, the rate of change of the relative Euler angles are related to the relative angular velocity by :

$$\begin{pmatrix} \dot{\phi}^{rel} \\ \dot{\theta}^{rel} \\ \dot{\psi}^{rel} \end{pmatrix} = \tilde{J}^{rel} \omega_b^{rel} \quad (\$5.2) \quad [A10]$$

where :

$$\tilde{J}^{rel} = \begin{pmatrix} 1 & \sin\phi^{rel}\tan\theta^{rel} & \cos\phi^{rel}\tan\theta^{rel} \\ 0 & \cos\phi^{rel} & -\sin\phi^{rel} \\ 0 & \sin\phi^{rel}\sec\theta^{rel} & \cos\phi^{rel}\sec\theta^{rel} \end{pmatrix} \quad [A11]$$

and :

$$\omega_b^{rel} = \omega_b^b - \tilde{L}_{bs} \omega_s^s \quad (\$5.2) \quad [A12]$$

with ω^s being the absolute angular velocity of frame s (relative to earth).

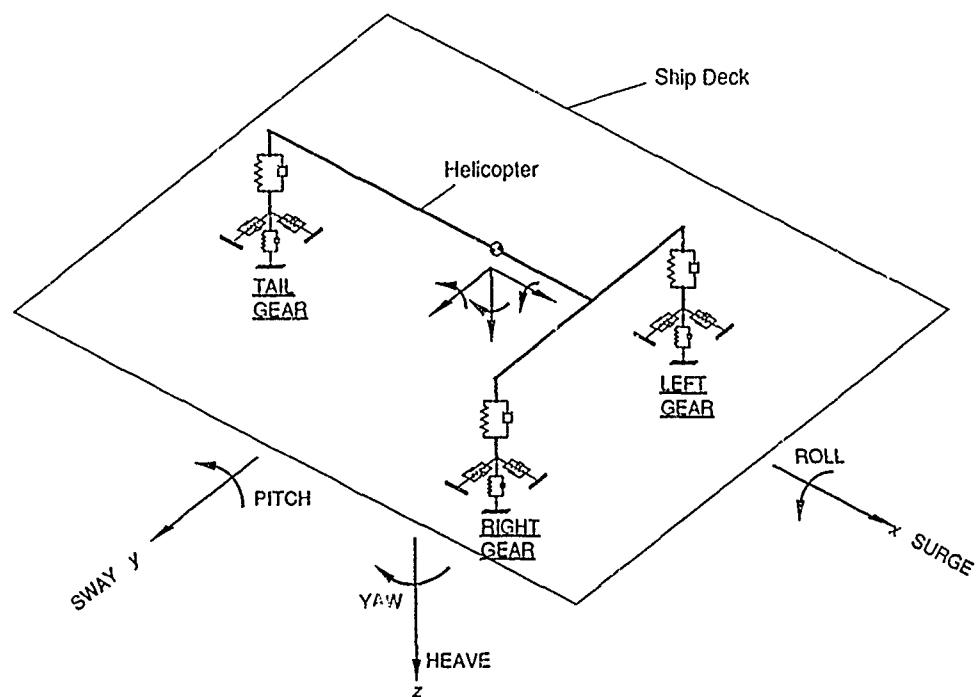


Figure 1. Schematic Diagram of Helicopter on Ship Deck

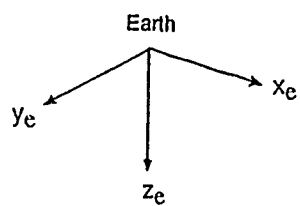
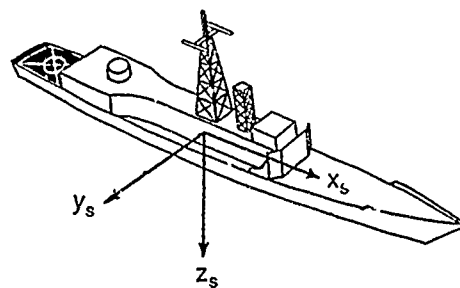
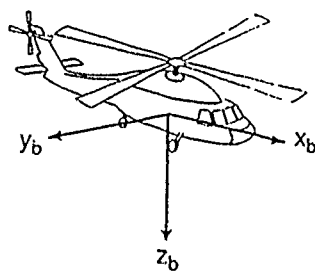


Figure 2. Axes Systems used

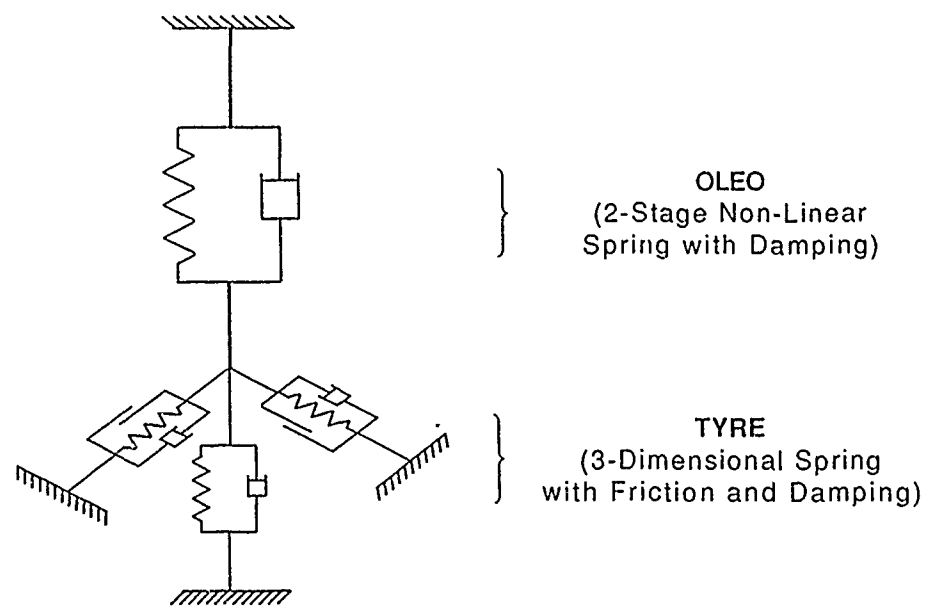
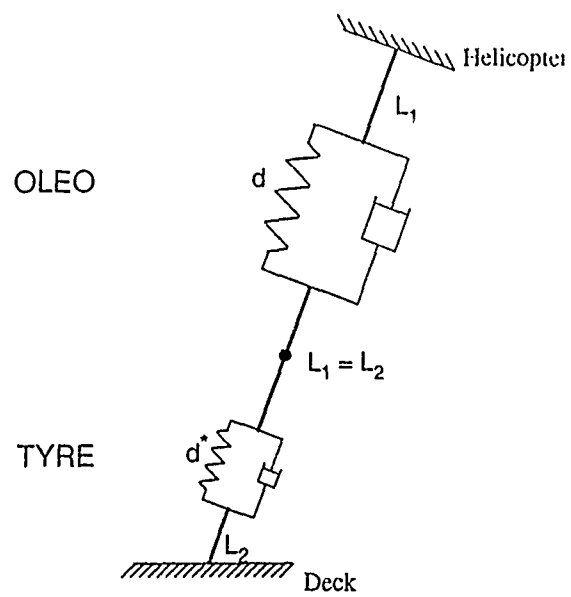


Figure 3. Mathematical Model of Oleo and Tyre



- L_1 = Oleo Load
- L_2 = Tyre Load
- d = Oleo Compression (z_b Direction)
- d^* = Tyre Compression (z_b Direction)
- $d+d^*$ = Total Gear Deflection (Oleo + Tyre)

Figure 4. Oleo and Tyre Loads and Deflections in Body z Direction

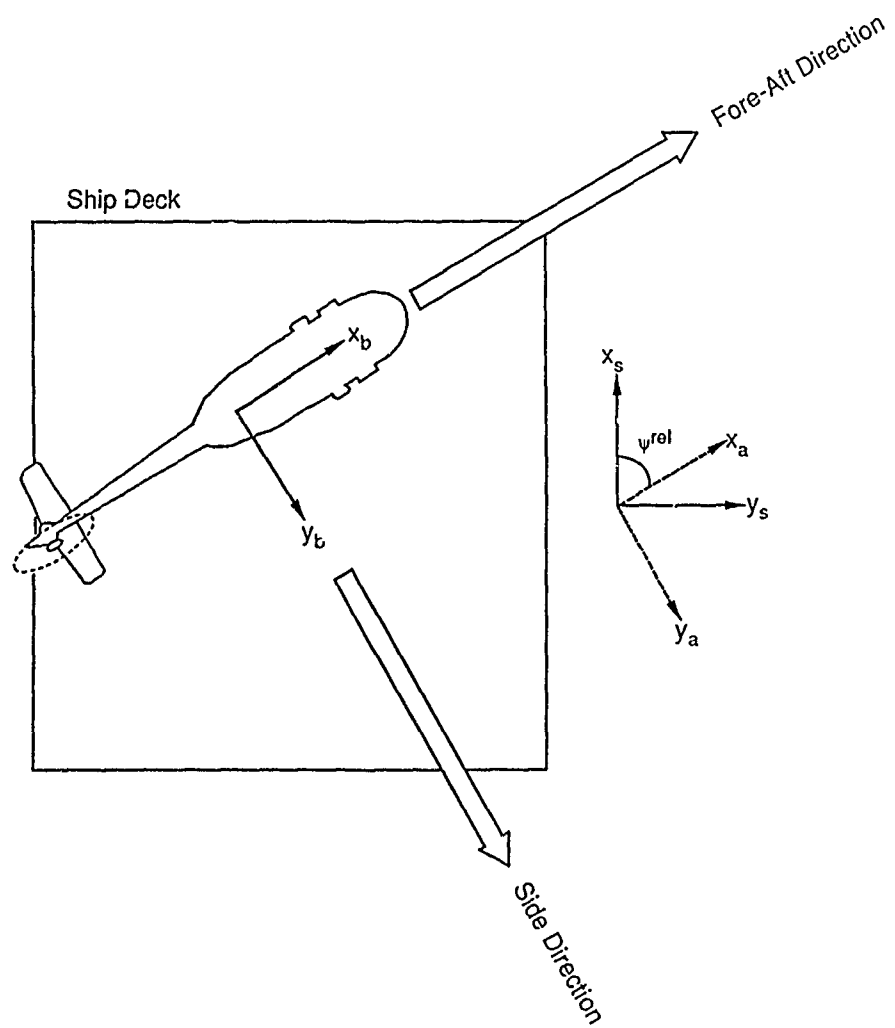


Figure 5. Relationship between Body Axes, Ship Axes and Aligned Axes

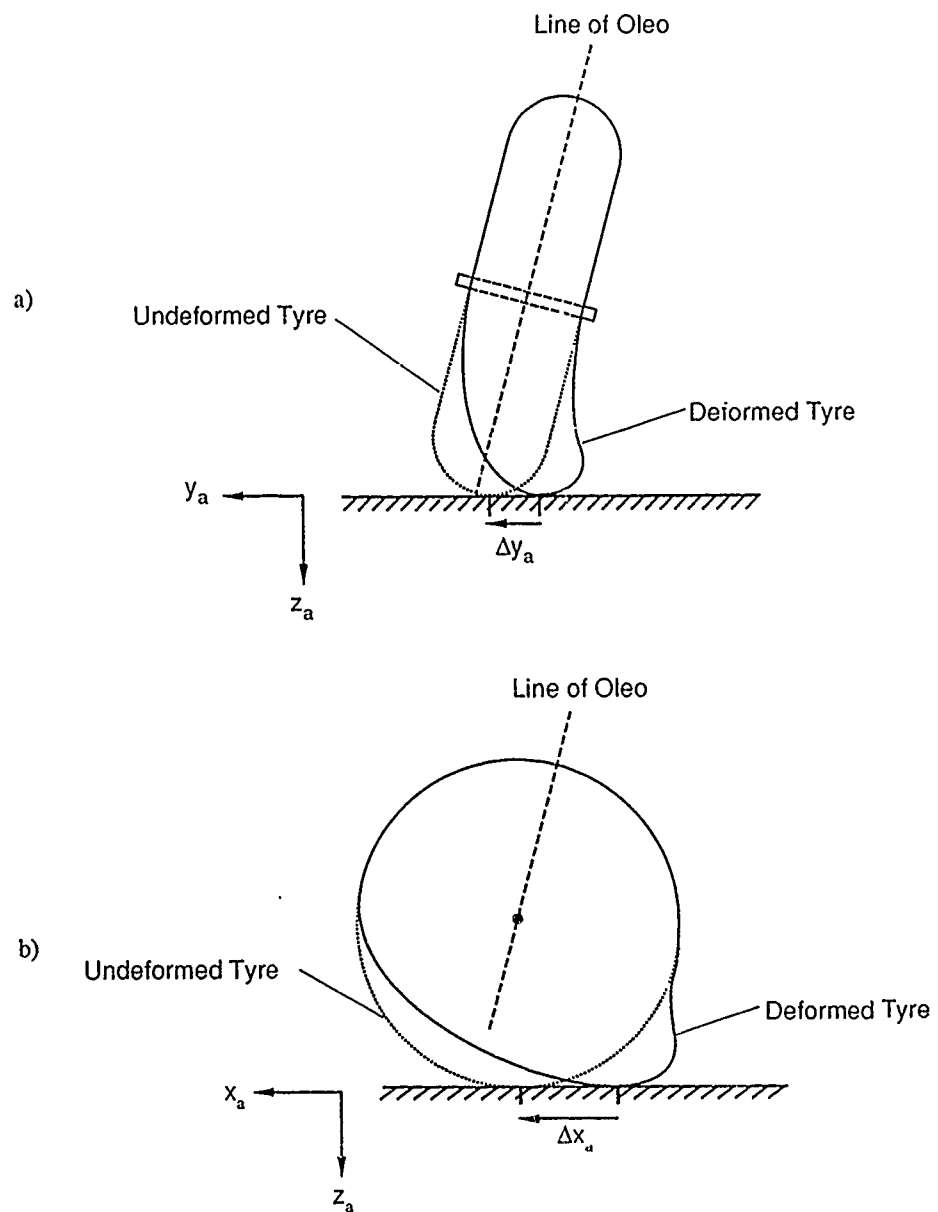


Figure 6. a) Tyre Deformation in Side (y_a) Direction, b) Tyre Deformation in Fore-Aft (x_a) Direction

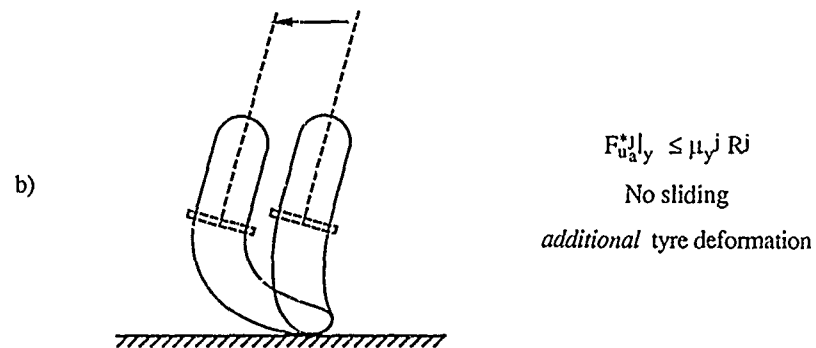
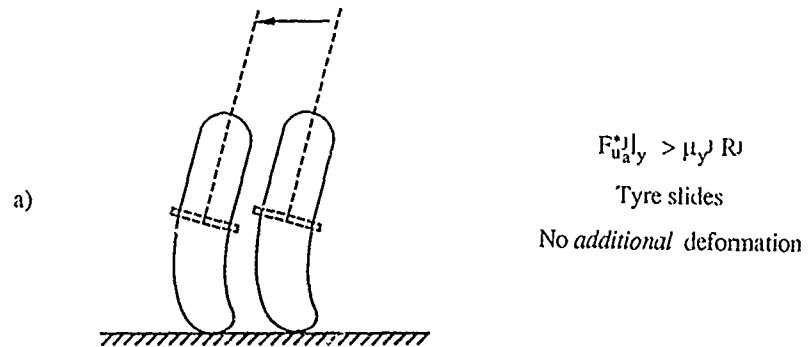


Figure 7. a) Tyre Sliding and b) Tyre Deformation in Sideways Direction (Tyre Dragging and Deformation in Fore-Aft Direction is Similar)

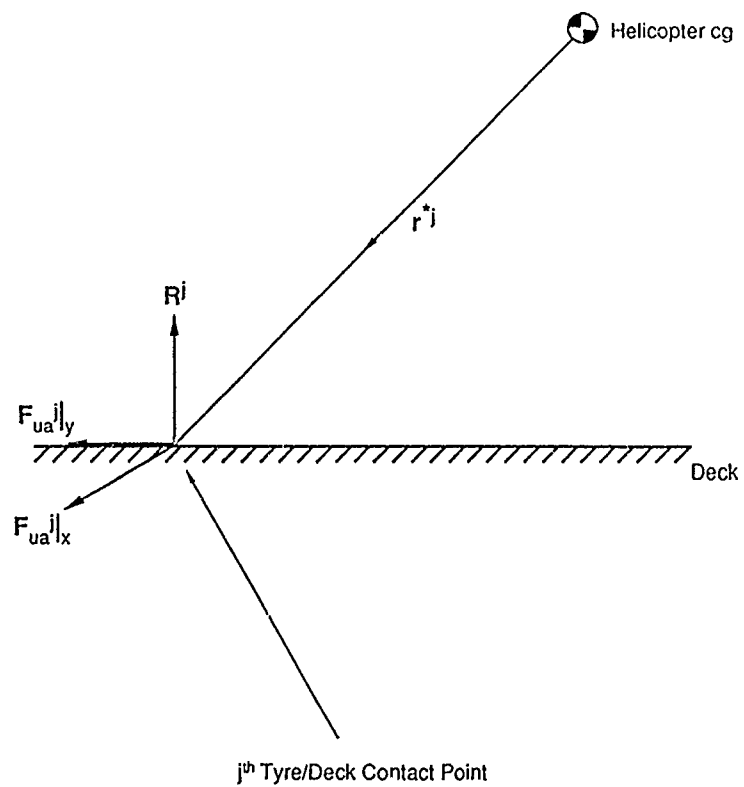


Figure 8. Forces due to j^{th} Gear

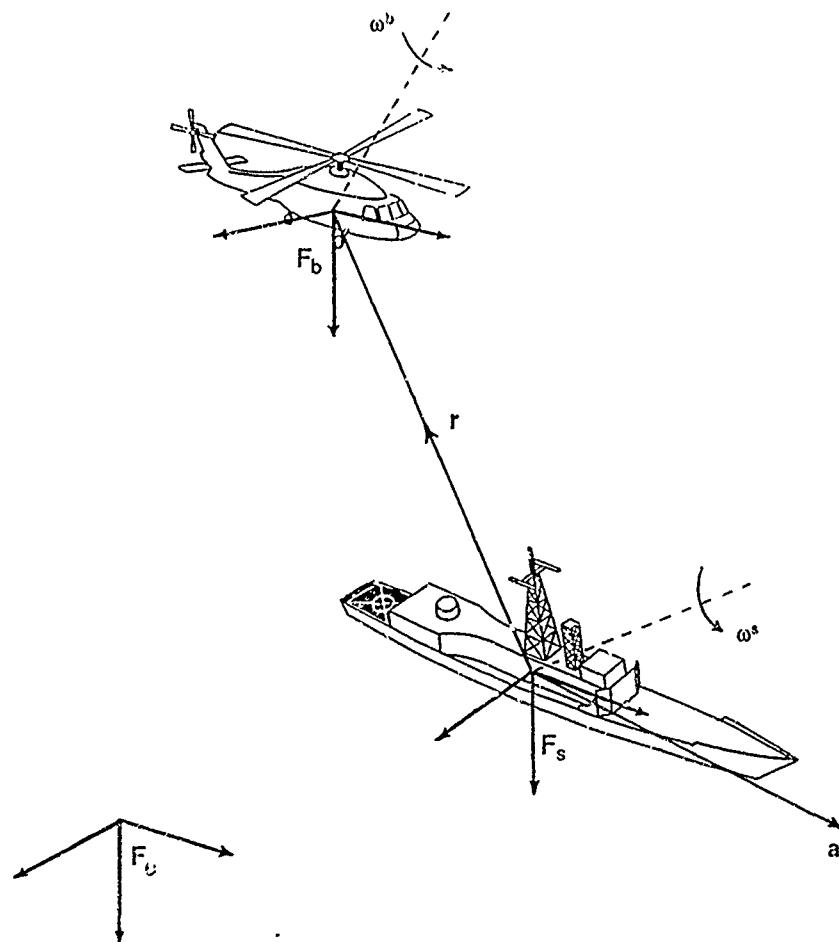


Figure 9. Relationship between Helicopter, Ship and Earth Axes

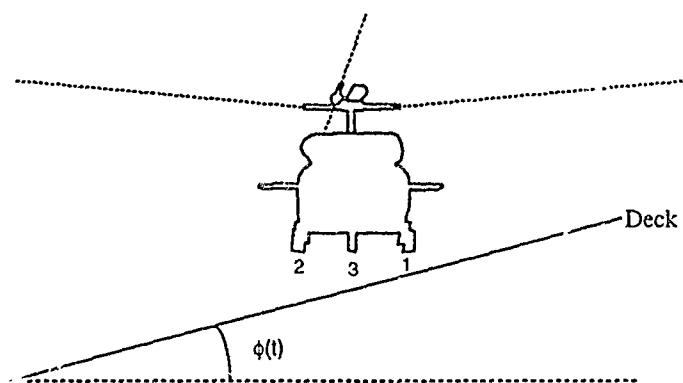


Figure 10. Helicopter "dropped" onto a Rolling Ship Deck

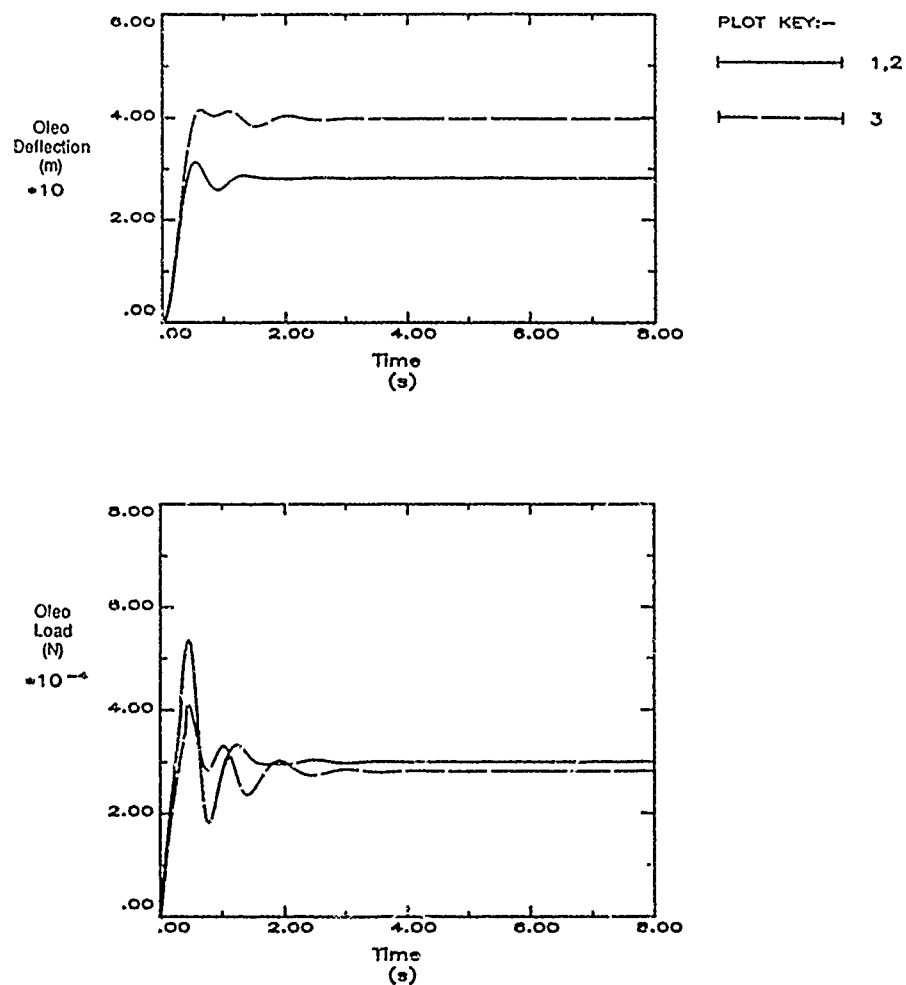


Figure 11. Oleo Deflection and Load for Helicopter "Dropped" onto Ship Deck.
Deck Horizontal and Stationary

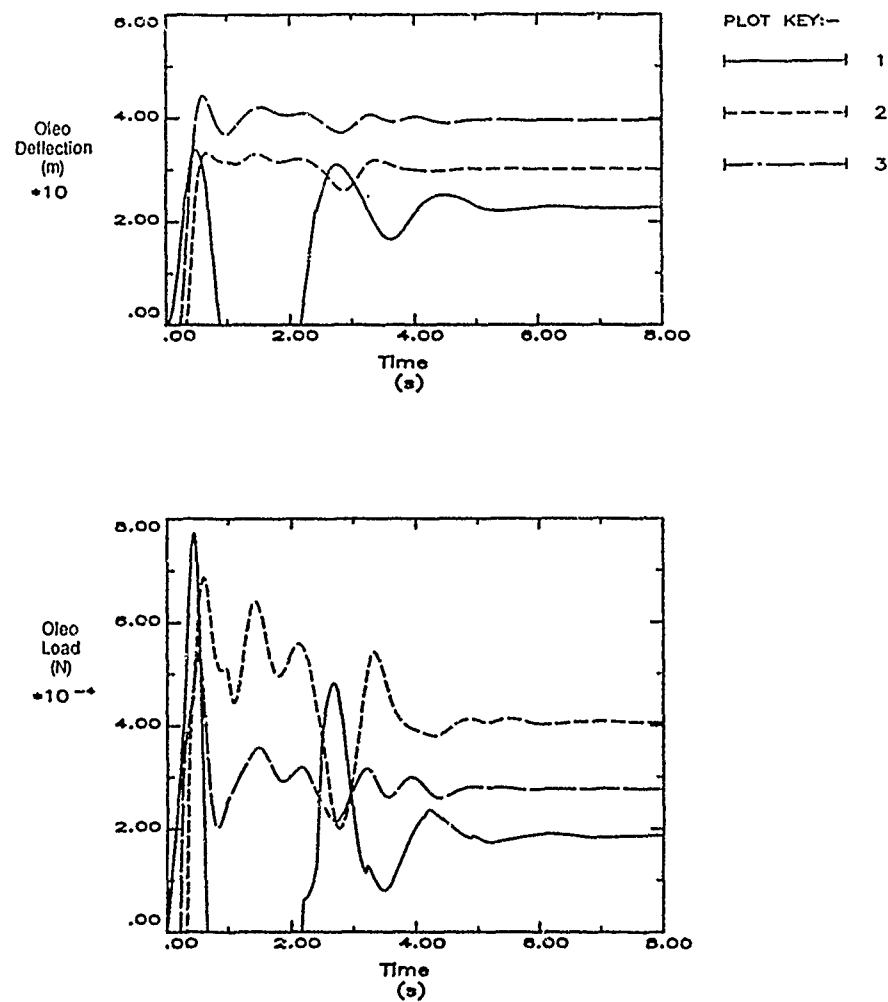


Figure 12. Oleo Deflection and Load for Helicopter "Dropped" onto Ship Deck.
Deck at 10° Roll and Stationary

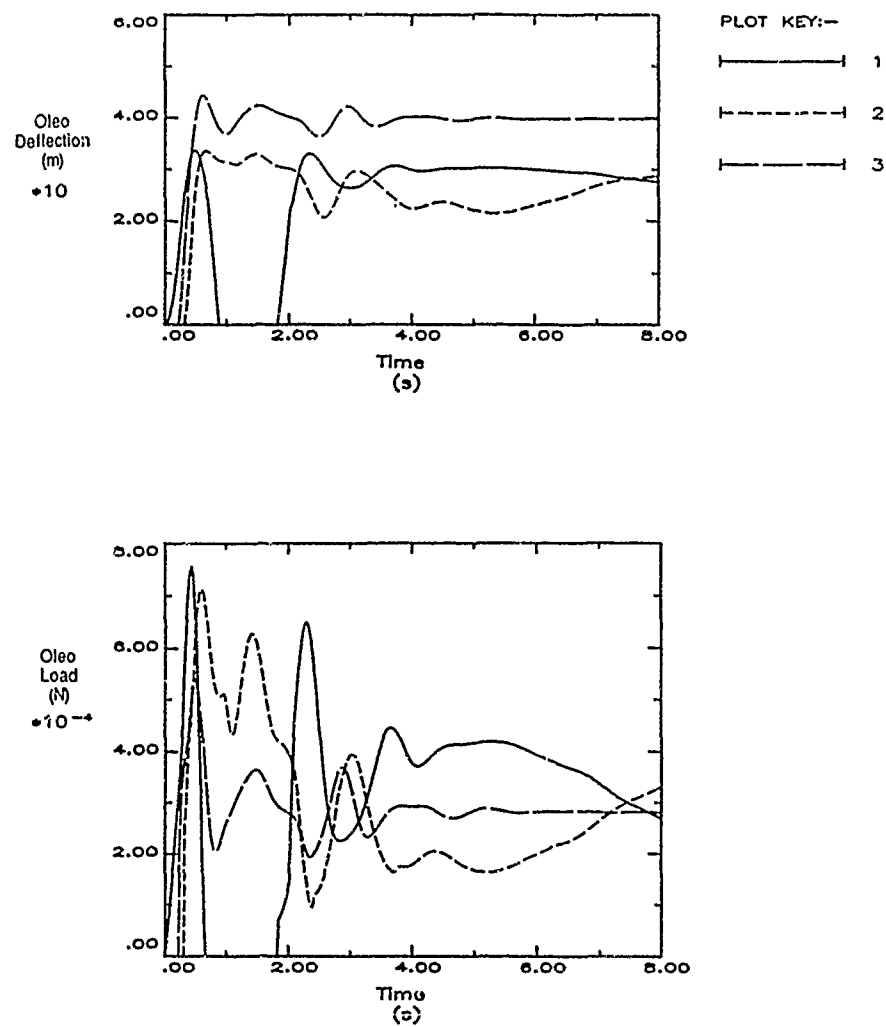


Figure 13. Oleo Deflection and Load for Helicopter "Dropped" onto Ship Deck. Deck Rolling Sinusoidally from -10° to $+10^\circ$ with Period 10 Seconds

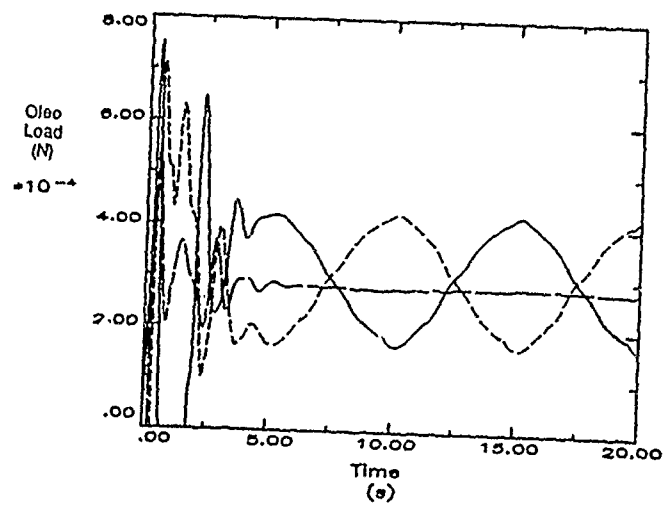
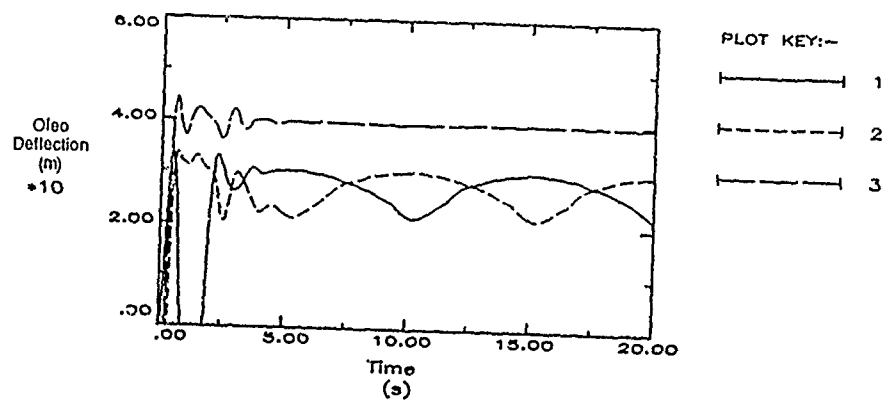


Figure 14. Oleo Deflection and Load for Helicopter "Dropped" onto Ship Deck. Deck Rolling Sinusoidally from -10° to $+10^\circ$ with Period 10 Seconds

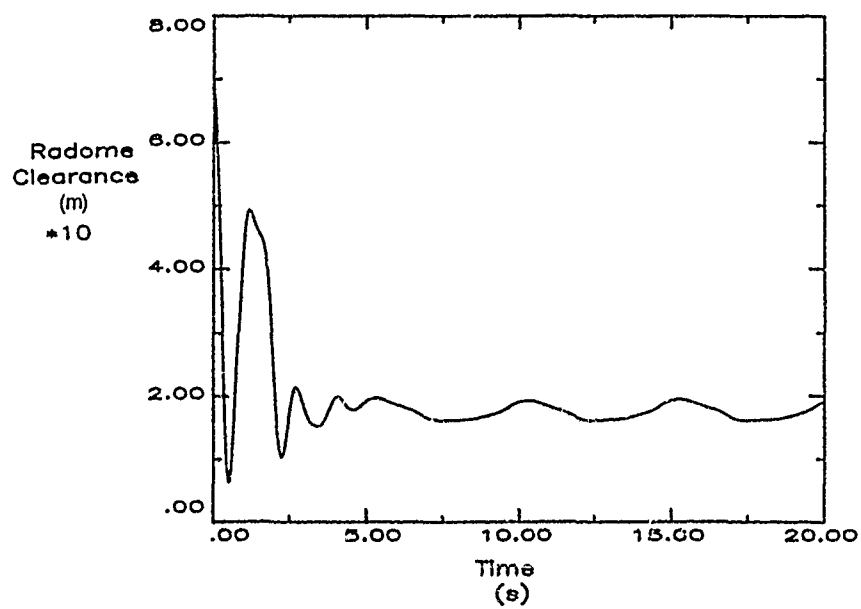


Figure 15. Deck Clearance of Radome.
Deck Rolling Sinusoidally from -10° to $+10^\circ$ with Period 10 Seconds

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16. ABSTRACT → A mathematical model of the on-deck helicopter/ship dynamic interface has been developed and implemented on an ELXSI 6400 computer. The purpose of this work is to provide a capability for investigating helicopter/ship dynamic interactions, such as deck clearances on landing, swaying, toppling and sliding criteria, and tie-down loads. Different helicopter types can be readily examined, given their undercarriage representation. The model takes account of arbitrary ship motion, and includes features such as brakes on or off, tyre deformation and tyre sliding. <u>Comments: Aircraft skidboard landings</u>			

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