INVESTIGATION OF THE RELATIONSHIP BETWEEN HELICOPTER GEOMETRICAL AND INERTIAL PARAMETERS AND SHIPBOARD SECURING REQUIREMENTS

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ABSTRACT

Extensive experience analyzing the securing requirements and on-deck stability of maritime helicopters on ships has revealed a strong dependence of securing requirements on aircraft configuration. While studies have been conducted comparing various in-service aircraft, interpretation of results has been complicated by significant differences in aircraft configurations. To overcome this difficulty, a parametric study was undertaken where controlled variations of key aircraft parameters were considered for three typical tricycle-configuration aircraft having nominal weights of 5 tonnes, 10 tonnes, and 15 tonnes. Parameters considered in the study were the aircraft mass, track width, wheelbase, longitudinal and vertical positions of the centre of gravity, magnitude of induced rotor loads, lateral projected area, and the vertical location of the centre of pressure. These eight parameters were varied using a 2^8 full-factorial experimental design and helicopter responses to two potentially severe ship motion conditions were predicted for each aircraft using the Indal Technologies Inc. *Dynaface* simulation software. The effect of the above parameters on landing gear reactions, vertical securing force, horizontal securing force, and relative angular motion were determined. Results were analyzed to determine the sensitivity of each outcome to each parameter individually and in all combinations for each aircraft and results were also analyzed to investigate trends in the sensitivities with aircraft size. Results demonstrate that securing requirements depend on aircraft configuration parameters and that in some cases the sensitivities increase significantly with aircraft weight. Detailed results are presented and discussed in this paper.

INTRODUCTION

Shipboard helicopter design is based on a wide range of considerations which include flying characteristics, landing performance, mission objectives, and economic factors. The large number of factors that influence the design of shipboard aircraft ensures variety in aircraft configurations that are proposed to satisfy the design constraints.

Numerous detailed simulation studies have been conducted by Indal Technologies Inc. (ITI), a developer of shipboard helicopter securing and handling equipment, for determining securing requirements for specific combinations of ship, aircraft, and operational requirements. A typical frigate, secured aircraft, and securing device are illustrated in Figure 1 through Figure 3 respectively. In the course of performing such analyses, it has been qualitatively and quantitatively observed that differences in helicopter configuration can significantly affect helicopter securing requirements, landing gear reaction forces, and relative displacements between the aircraft and ship deck in the presence of severe yet routine ship motion. These investigations have generally been based on a single existing or proposed helicopter configuration and typically did not address the influence of changes in configuration parameters on securing requirements.

However, with ever-increasing global requirements to operate larger aircraft, on smaller ships, and in increasingly severe sea conditions, a better understanding of the relationships between aircraft configuration and securing requirements is clearly motivated. Two approaches are possible for quantifying the effect of helicopter configuration on shipboard securing performance. The first involves considering a variety of currently in-service aircraft and assessing differences in securing requirements for a standardized set of ship motion inputs. This approach benefits from using actual aircraft configurations but is complicated by multiple differences in configuration between aircraft. This approach has however been successfully applied by developing and using sets of nondimensional parameters and various additional performance measures for quantifying the relative perfor-

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mance of representative shipboard aircraft. The second approach involves performing sensitivity studies where small variations on existing aircraft configurations are considered in isolation or in controlled combination with other concurrent configuration changes. This approach permits varying parameters in a carefully controlled way. However, it implicitly compares potential, rather than existing, configurations.

The results of a pilot study based on the latter approach and using a nominally 10 tonne generic tricycle-configuration aircraft and a typical frigate were recently published [1]. The results provided insight into the basic relationships between configuration and securing requirements and confirmed the qualitative observations that previously had been made. One aspect that the pilot study did not address was whether the results obtained could be generalized to other aircraft of significantly different size. That is the focus of the current investigation.

Figure 1. Typical 135 metre frigate

Figure 2. Typical shipboard securing condition

Figure 3. ITI ASIST securing system

The current study expands on the methodology developed in the pilot study and generalizes the analysis to assess the sensitivities of securing requirements of generic forms of 5, 10, and 15 tonne helicopters to changes in geometrical and inertial parameters. The parameters that are considered are helicopter mass, track width, wheelbase, longitudinal and vertical positions of the centre of mass, magnitude of induced rotor loads, lateral projected area of the fuselage, and height of the fuselage centre of pressure above the deck.

While it is widely known that a variety of conditions affect the securing requirements for a helicopter on a frigate-sized ship such as the one illustrated in Figure 1, the effects of ship design have been discussed extensively in Reference 2, the effect of sea conditions and ship operating conditions have been addressed to some extent in Reference 3, and the effect of the securing concept used has been discussed in Reference 4. As a result, this study addresses the helicopter configuration exclusively.

Subsequent sections present a comparison of the basic helicopter configurations that are used in the study, a brief overview of the simulation and analysis methodology, description of the parametric study focused on geometrical and inertial parameters, results for the three aircraft, and finally discussion and conclusions addressing dependencies of sensitivities on aircraft size.

BASIC AIRCRAFT CONFIGURATIONS

As mentioned previously, three sizes of helicopters, 5 tonne, 10 tonne, and 15 tonne, are used in the study. The helicopter arrangement is based on a general tricycle configuration with a nose wheel as shown in Figure 4.

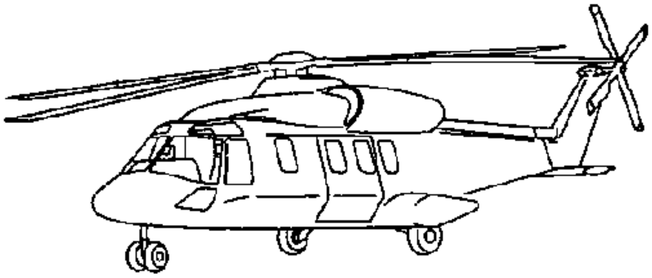


Figure 4. Typical tricycle-configuration helicopter

Effort was made to utilize helicopter characteristics that match the helicopter size. However, as a generic study, the characteristics of the helicopters used in the study may not reflect the exact performance of the corresponding in-service helicopters.

To investigate the effect of the helicopter configuration on its response to the ship motion, a set of basic parameters describing the various aspects of a generic helicopter are defined in Table 1.

In addition, several factors defined in Table 2 were derived from the helicopter geometrical and inertial parameters defined in Table 1 and Figure 5 to help establish relationships between the helicopter response to the ship motion and the helicopter configuration. These factors have been shown to affect the securing requirements from previous studies, under the worst case ship motion conditions.

ANALYSIS METHODOLOGY

Figure 2 shows a typical embarked helicopter secured to the deck by a rapid securing device (RSD). The RSD is part of an ITI Aircraft/Ship Integrated Secure and Traverse (ASIST) system which secures the helicopter from a helicopter-mounted probe as shown in Figure 3.

During various on-board operations, helicopter excitation results primarily from time-dependant landing gear and securing forces as well as induced aerodynamic forces. These forces depend on characteristics of the ship, characteristics of the aircraft, and specific operating conditions. To develop an adequate description of the dynamic loading appropriate for analysis, transient dynamic computer simulation of the interface between the secured aircraft and the ship is required. An appropriate simulation model has been developed and is implemented in ITI's *Dynaface*® simulation package [5]. The simulation produces time histories of generalized forces and generalized displacements at the interface between the aircraft and ship in response to ship motion and aerodynamic loading.

The *Dynaface* simulation uses a special-purpose 15-degree-of-freedom mathematical model of the aircraft/ship system. The degrees of freedom are comprised of three translations and three rotations for the ship, three translations and three rotations for the aircraft body, and one prismatic or revolute degree of freedom per suspension station, depending on the suspension type. Forces acting on the aircraft portion of the system include deck reaction forces, securing forces, aerodynamic forces, inertial forces, and gravitational forces. Seven primary coordinate systems are used to derive the equations of motion: an inertial frame, a ship frame, an aircraft frame, a rotor tip path plane frame, and wheel frames corresponding to each suspension station (maritime aircraft have at least one steerable or castorable wheel). The simulation then generates the time-varying prescribed ship motion and propagates a time-domain solution by numerically integrating the governing Newton-Euler equations of motion for the system. While the simulation is special-purpose to promote solution efficiency, it includes sufficient generality such that a large variety of aircraft and virtually all ships can readily be modelled. The simulation currently contains prismatic oleo and leading/trailing arm suspension models having up to two wheels each that can be attached to the fuselage in either nose-wheel or tail-wheel configurations, up to two main rotors, and a large variety of possible securing devices. The model includes detailed representation of the oleo stiffness, damping, and friction characteristics; induced rotor forces; and a nonlinear tire model that supports complex tire behaviour including lift-off and touch-down, rolling due to suspension travel, brake slippage, and sliding. An exhaustive set of optional results; including aircraft relative angular displacements, securing forces, landing gear reaction forces, suspension forces and displacements, tire deflections, induced aerodynamic forces, and animation data are saved in a selected subset of 21 available output files. Simulation results are post-processed by a suite of utility programs or animated using either two- or three-dimensional dedicated animation software tools. The *Dynaface* simulation has been validated by comparison with other simulation results, analytical solutions, rig suspension drop test results, and both land-based and sea trial experimental results.

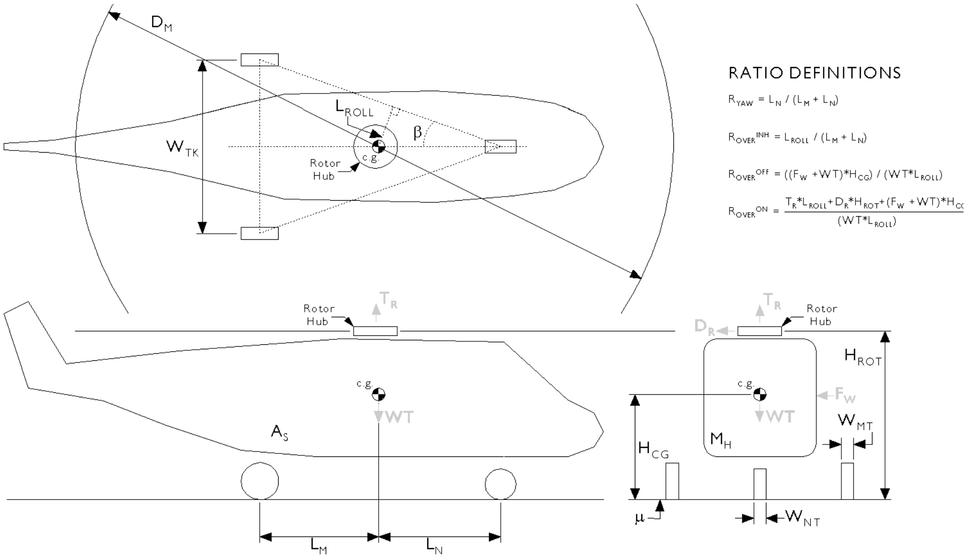
Typical securing force simulation studies are begun by generating six-degree-of-freedom ship motions for the applicable ship and operating conditions for extended time periods using well-established linear frequency-domain ship simulation methods and software [6, 7]. For the current investigation, ship motion was generated for the frigate shown in Figure 1. The sea conditions were selected to correspond to upper sea state 5 characterized by a significant wave height of 4 metres and a wave modal period of 11 seconds [8]. Ship headings varied from 0° through 180° in 15° increments and a range of ship speeds were considered.

Table 1. Parameters characterizing helicopter configurations

PARAMETERS HELICOPTER SPECIFICATIONS	UNIT	SYMBOL	HELICOPTERS AND CONFIGURATIONS		
HELICOPTER MASS	kg	M_H	15000	10000	5000
C.G. HEIGHT	m	H_{CG}	2.36	1.73	1.50
MAIN ROTOR DIAMETER	m	D_M	18.60	16.00	12.80
HEIGHT OF THE ROTOR HUB	m	H_{ROT}	4.81	4.03	2.69
ROTOR INDUCED THRUST AT 20°, 30 kts WIND	kN	T_R	26.69	5.00	4.16
ROTOR INDUCED DRAG AT 20°, 30 kts WIND	kN	D_R	0.95	0.07	0.02
EQUIVALENT SIDE AREA	m^2	A_S	57.00	31.00	18.00
TRACK WIDTH	m	W_{TK}	4.28	3.20	2.78
MAIN GEAR TIRE WIDTH	m	W_{MT}	0.22	0.23	0.14
NOSE/TAIL TIRE WIDTH	m	W_{NT}	0.14	0.15	0.11
M/G to C.G. DISTANCE	m	L_M	1.95	1.67	1.09
N(T)/G to C.G. DISTANCE	m	L_N	5.04	4.24	1.93
OTHER SPECIFICATIONS	**UNIT**	**SYMBOL**			
DECK FRICTION COEFFICIENT		μ	0.60	0.60	0.60
MODAL PERIOD	s	T_{MODAL}	11.00	11.00	11.00
AIR DENSITY	kg/m^3	ρ	1.23	1.23	1.23
WIND SPEED	knots	V_{WIND}	30.00	30.00	30.00
FUSELAGE DRAG COEFFICIENT		C_D^{FUS}	1.00	1.00	1.00

Table 2. Parameters affecting helicopter/ship dynamic interface

DERIVED FACTORS	UNIT	SYMBOL	EQUATION	HELICOPTERS AND CONFIGURATIONS		
HELICOPTER WEIGHT	kN	WT	MH*g / 1000	147.10	98.07	49.03
HELICOPTER STANDARDIZED WEIGHT RATIO		RWTSTD	WT / WT(5 tonne)	3.00	2.00	1.00
FUSELAGE AERODYNAMIC DRAG	kN	FW	(CDFUS * ½rVWIND2AS) / 1000	8.32	4.52	2.63
LANDING GEAR ANGLE	°	b	atan(0.5*WTK/(LM+LN))	17.01	15.15	24.73
ROLL OVER MOMENT ARM	m	LROLL	LN*sin(b)	1.48	1.11	0.81
M/G STATIC REACTION	kN	RSVM	(WT*LN / (LM+LN)) / 2	53.01	35.18	15.66
N(T)/G STATIC REACTION	kN	RSVN	WT*LM / (LM+LN)	41.07	27.72	17.71
ROTOR LOADING	kN/m2	FROT	WT / DM2	0.43	0.39	0.31
FUSELAGE LATERAL AERODYNAMIC LOADING	kN/m2	FFUS	FW / AS	0.15	0.15	0.15
ROTOR LIFT TO DRAG COEFFICIENT RATIO		CDROT/CLROT	DR/TR	0.04	0.01	0.004
M/G LOADING RATIO		RMLR	RSVM / (WTK*g/1000)	0.36	0.36	0.32
N/G LOADING RATIO		RNLR	RSVN / (WTK*g/1000)	0.28	0.28	0.36
N/G TO M/G RATIO		RNMR	RNLR / RMLR	0.77	0.79	1.13
SIDE AREA TO ROTOR AREA RATIO		RAREA	AS* / (pDM2/4)	0.21	0.15	0.14
ROTOR THRUST TO TOTAL RXNS. RATIO		RTH	TR / (RSVN + 2*RSVM)	0.18	0.05	0.08
ROLL OVER RATIO - ROTOR OFF		ROVEROFF	((FW+WT)*HCG) / (WT*LROLL)	1.69	1.64	1.96
ROLL OVER RATIO - ROTOR ON		ROVERON	(TR*LROLL+DR*HROT+(FW+WT)*HCG) / (WT * LROLL)	1.89	1.69	2.05
ROLL OVER RATIO - INHERENT		ROVERINH	LROLL / (LM+LN)	0.21	0.19	0.27
YAW TENDENCY RATIO		RYAW	LN / (LM+LN)	0.72	0.72	0.64



$R_{YAW} = L_N / (L_M + L_N)$

$R_{OVER}^{INH} = L_{ROLL} / (L_M + L_N)$

$R_{OVER}^{OFF} = ((F_W + WT)*H_{CG}) / (WT*L_{ROLL})$

$R_{OVER}^{ON} = \frac{T_R*L_{ROLL}+D_R*H_{ROT}+(F_W + WT)*H_{CG}}{(WT*L_{ROLL})}$

Figure 5. Helicopter parameters and factors affecting securing requirements

To ensure that statistically significant severe motions were included in the simulated time period, ship simulations were run for 30,000 seconds (8.33 hours). The ship motion results were then analyzed to identify operating conditions that were expected to produce some of the most demanding conditions for helicopter securing. Figure 6 shows the ship motion polar plot for roll angle at a ship speed of 15 knots and Figure 7 shows the plot for equivalent acceleration ratio. The peak ship roll angle occurs in quartering seas at a ship heading of 120° relative to the principal wave direction while the peak equivalent acceleration ratio occurs in beam seas at a heading of 75°. The equivalent acceleration ratio is the ratio of the total horizontal acceleration of a point at the centre of the flight deck to the total vertical acceleration expressed in a ship-fixed coordinate system. It is known that high values of this ratio correspond to demanding securing conditions. This concept has been discussed at length in Reference 4.

The helicopter response simulation involved using the above-selected two ship motion cases as input to *Dynaface* that was run for each permutation of helicopter configuration parameters. A 27-knot beam wind was used for all simulation cases, representing the wind condition associated with upper sea state 5 [8]. The generalized force and displacement outputs were then post-processed to identify the peak values that occurred during 3600 seconds (1 hour) of simulated helicopter response to deck motions. This time period was chosen to be sufficient to ensure statistically meaningful results [6].

PARAMETRIC STUDY

The parametric study varies key parameters that, based on experience, were perceived to affect on-deck securing requirements. Those were (as introduced previously): aircraft mass and mass moments of inertia (mass), track width (tk_wdh), wheelbase (wh_bs), longitudinal position of the centre of gravity (CGx), vertical position of the centre of gravity (CGz), induced rotor loads (rtr), aircraft projected side area (y_area), and vertical location of the centre of pressure (CPz). Simulations were run for all permutations of two levels of these eight parameters. The lower level was the nominal value for the generic aircraft of the particular weight and the upper level was 20% above the nominal value. The study was repeated for both the peak roll and peak equivalent acceleration ratio[1] ship motion cases. This resulted in a total of 512 simulation cases for each aircraft (2^8 simulations run for each of two ship motion cases).

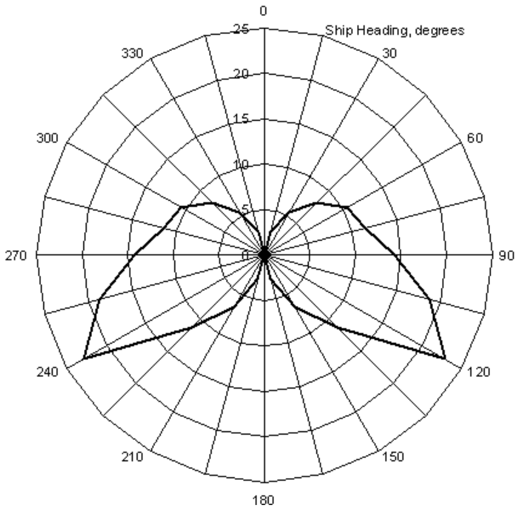


Figure 6. Peak ship roll angle [deg] as a function of ship heading corresponding to upper sea state 5 and a ship speed of 15 knots

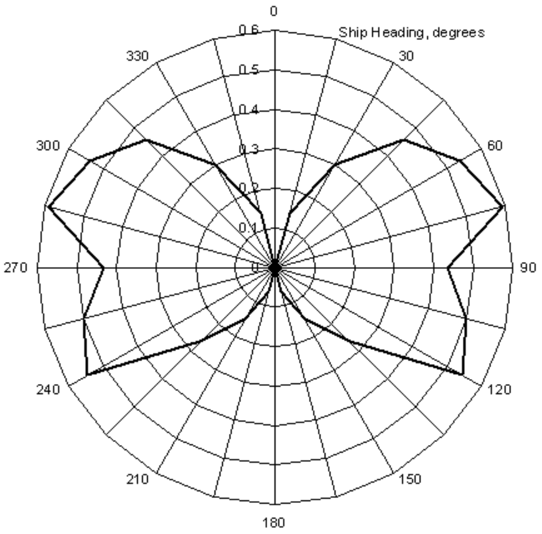


Figure 7. Peak ship ratio of horizontal equivalent to vertical equivalent acceleration as a function of ship heading corresponding to upper sea state 5 and a ship speed of 15 knots

Simulation results were post-processed to extract the peak landing gear vertical reaction (LGR), vertical component of the main probe securing force (MPZ), resultant of the longitudinal and lateral components of the main probe securing force (MPR), and relative orientation angle between the aircraft and the ship flight deck (ANG).

RESULTS

The objective of the 2^8 factorially-designed experiment was to assess the impact of each of the eight aircraft parameters

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[1] The equivalent acceleration ratio case will subsequently be referred to simply as the acceleration case.

on the four conventional measures of securing requirements (identified in the previous section) as a function of aircraft weight. This was accomplished by first performing a Yates analysis [9, 10] on each of the four peak value data sets arising from both the roll and acceleration ship motion cases for each aircraft. The analysis resulted in the effect attributable to each of the eight parameters individually as well as in all combinations of two through eight parameters. In this way, the effects of individual parameters as well as their interdependencies could be identified. The force results were nondimensionalized by the nominal aircraft weight and expressed as a change in force as a percentage of the aircraft weight. The angular results were nondimensionalized by the average of the nominal relative angles obtained from the roll and acceleration cases. The sign of individual results indicates whether specific parameters or combinations of parameters lead to an increase (positive) or decrease (negative) in the securing force or relative angle. Figure 8 shows the sensitivities for the four effects for each parameter or combination of parameters (255 in total as 1 simulation case represented the nominal case) for the roll ship motion case and the 10 tonne aircraft. As can be seen from the figure, many effects (particularly combinations of parameters) are negligible. Similar results were obtained for the acceleration motion case. Similar results were also obtained for the 5 tonne and 15 tonne aircraft. It should be recalled that the sensitivities are the percent change in effect resulting from 20% changes in parameter values.

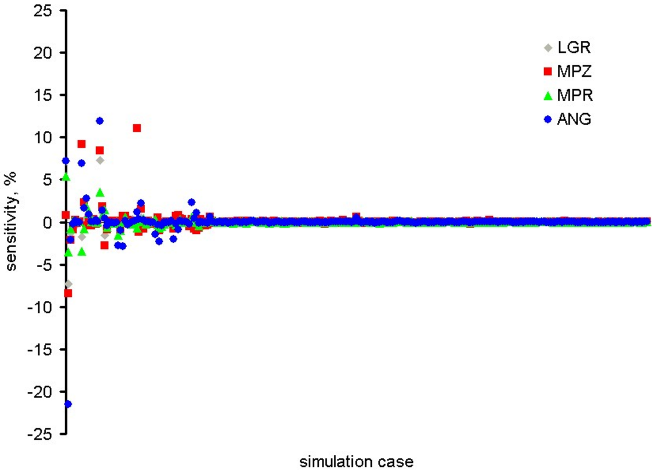

Figure 8. Graphical summary of simulation results for the roll ship motion case and the 10 tonne aircraft

An approach was required to determine the threshold values above which results must be considered significant. Provided the roll and acceleration cases produced consistent results for the sensitivities, comparison of these two cases could be used to obtain the standard error on effects [9] and those values could be used as the threshold for identifying significant results. To check for this agreement, the percentage change in effects resulting from the acceleration motion case were plotted against the corresponding values for the roll case for each of the four outcomes. The resulting correlation plots, including data for each of the three aircraft, for vertical landing gear reaction, vertical probe force, radial probe force, and relative angle are presented in Figure 9 through Figure 12 respectively. A line representing perfect agreement between the two corresponding sets of results is shown on each plot. Agreement between the data and the trend lines indicates consistent results independent of the motion case considered whereas dispersion indicates results are only somewhat dependent on the motion case considered. From the figures it is apparent that the landing gear reaction, vertical probe force, radial probe force, and relative angle effects agree reasonably well between motion cases, with the greatest dispersion observed for the radial probe force[2]. Based on this comparison, the calculation of standard errors was performed resulting in levels of significance provided in Table 3.

The sensitivities of primary effects resulting from the roll case and the acceleration case are compared graphically for the 5, 10, and 15 tonne aircraft in Figure 13 through Figure 15 respectively. In these figures, columns indicate the mean of the roll and acceleration case results and the error bands indicate the corresponding roll and acceleration case values. From these results it was found that both motion cases tended to produce similar sensitivities. As a result, the average effect of each parameter was used for subsequent analysis and discussion.

Table 4 through Table 6 contain the average effects of 20% increases in each of the eight parameters on each of the four outcomes considered. The shaded values indicate magnitudes below the corresponding standard error provided in Table 3 that should not be considered significant. As an example of the interpretation of the data contained in these tables, consider the MPZ column in Table 6. It indicates that a 20% increase in mass would increase the vertical securing force requirement by approximately 20%; a 20% increase in track width would decrease the force by approximately 39%; moving the centre of gravity forward by 20% would increase the force by approximately 35%; and increasing the centre of gravity height by 20% would increase the force by approximately 37%. Considering instead the second row indicates that increasing the track width by 20% would reduce the landing gear reaction by 23%, the vertical securing force by approximately 39%, the radial securing force by

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[2] It should be noted that in these plots 100% corresponds to the effects arising from the nominal design condition. It is observed that the parameter variations considered at times produced significantly more or less severe securing conditions than the nominal aircraft configuration.

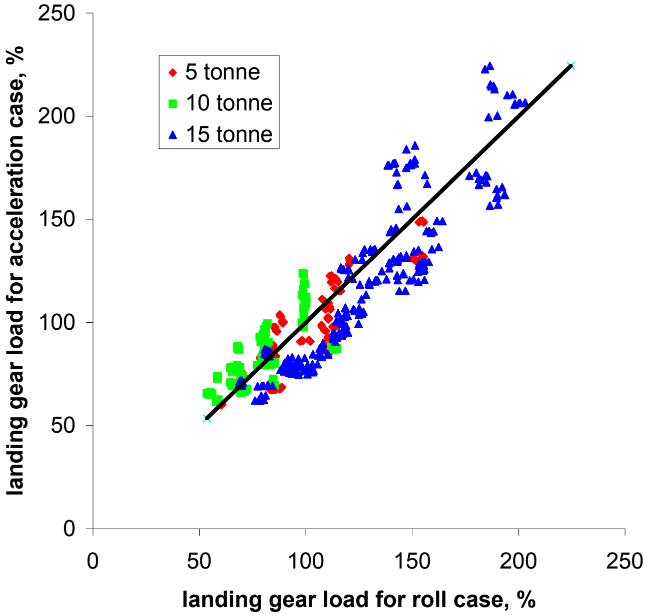

Figure 9. Correlation of peak vertical landing gear reaction forces between peak ship roll and peak ship equivalent acceleration motion cases

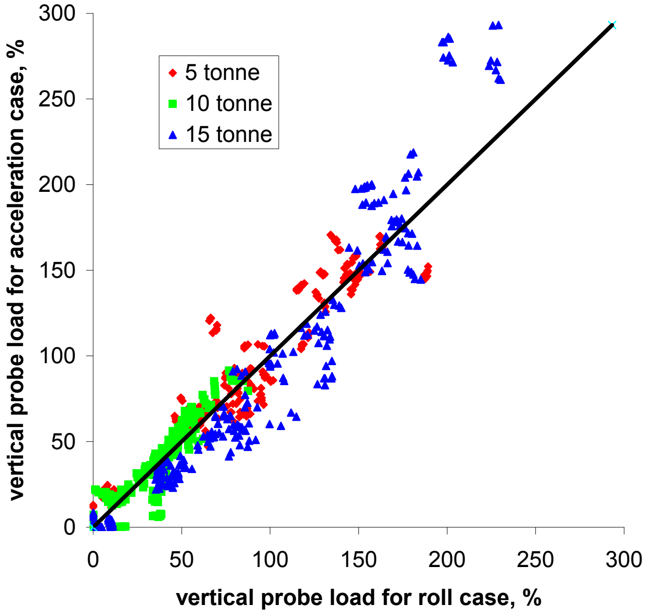

Figure 10. Correlation of peak vertical securing forces between peak ship roll and peak ship equivalent acceleration motion cases

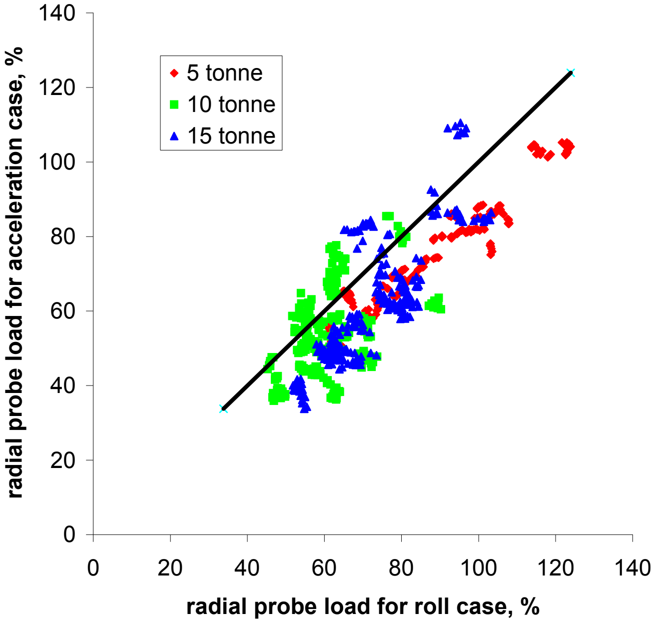

Figure 11. Correlation of peak radial securing forces between peak ship roll and peak ship equivalent acceleration motion cases

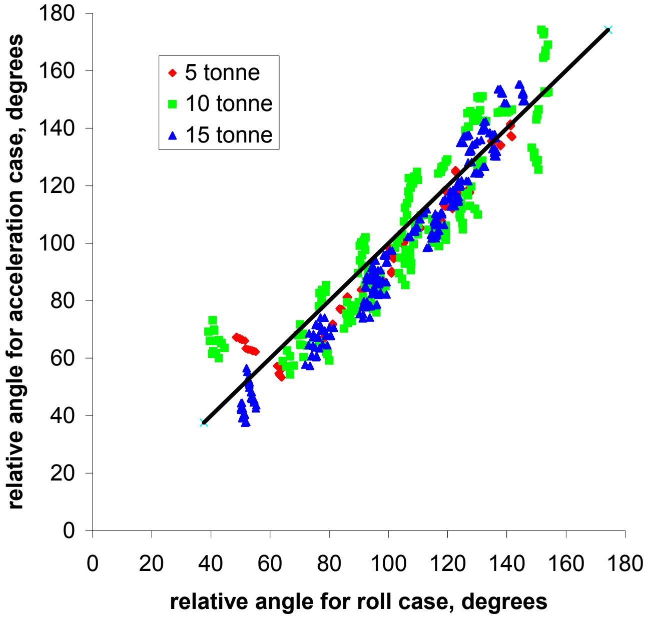

Figure 12. Correlation of peak relative angular displacements between peak ship roll and peak ship equivalent acceleration motion cases

Table 3. Standard errors for each aircraft and mean values

Aircraft	LGR,%	MPZ,%	MPR,%	ANG,%
5 tonne	6.1	6.4	4.9	6.2
10 tonne	5.1	2.7	3.4	6.7
15 tonne	7.6	7.7	3.9	6.4
mean	6.3	5.6	4.1	6.4

approximately 9%, and the relative angular displacement by approximately 22%.

Table 4. Average effect of single-parameters for 20% change in parameter values for 5 tonne helicopter

Parameter	LGR,%	MPZ,%	MPR,%	ANG,%
mass	12.7	14.9	9.2	7.4
tk_wdh	-11.4	-23.3	-8.8	-18.0
wh_bs	-2.6	-4.7	-0.1	-1.8
CGx	6.7	19.2	2.8	4.9
CGz	13.1	27.6	6.6	11.4
rtr	0.0	-0.5	0.0	0.0
y_area	0.0	-0.1	0.0	0.0
CPz	0.0	-0.2	0.0	0.0

Table 5. Average effect of single-parameters for 20% change in parameter values for 10 tonne helicopter

Parameter	LGR,%	MPZ,%	MPR,%	ANG,%
Mass	7.4	0.9	5.0	6.9
tk_wdh	-6.7	-9.7	-4.8	-21.9
wh_bs	-1.0	-1.6	-0.1	-1.1
CGx.	1.5	10.8	-0.2	8.2
CGz	6.4	9.3	4.3	11.9
Rtr	0.6	9.9	1.9	3.5
y_area	0.3	0.1	0.3	0.3
CPz	0.3	0.1	0.0	0.3

Table 6. Average effect of single-parameters for 20% change in parameter values for 15 tonne helicopter

Parameter	LGR,%	MPZ,%	MPR,%	ANG,%
mass	16.4	19.9	7.5	7.5
tk_wdh	-23.0	-38.8	-8.9	-22.1
wh_bs	-1.9	-4.8	-0.8	-1.7
CGx	9.3	34.8	1.6	10.7
CGz	21.1	36.6	7.0	12.9
rtr	0.7	0.5	0.0	0.2
y_area	-1.1	-2.5	-0.1	-0.8
CPz	-1.2	-2.9	0.0	-0.9

The significant results from Table 4 through Table 6 have been presented graphically for each outcome as a function of helicopter weight in Figure 16 through Figure 19.

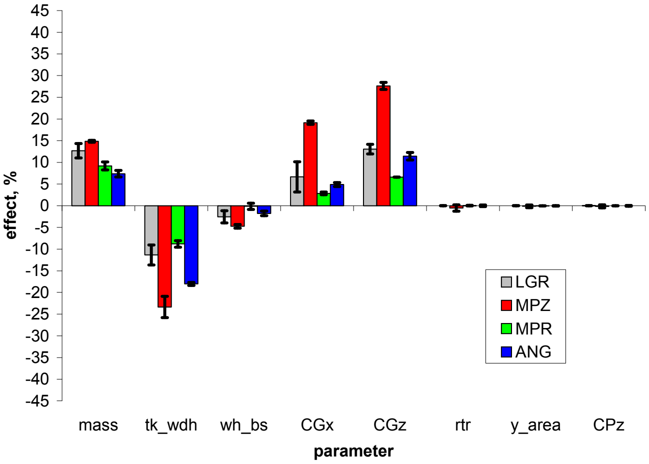

Figure 13. Effect of 20% changes in single parameter values for 5 tonne helicopter

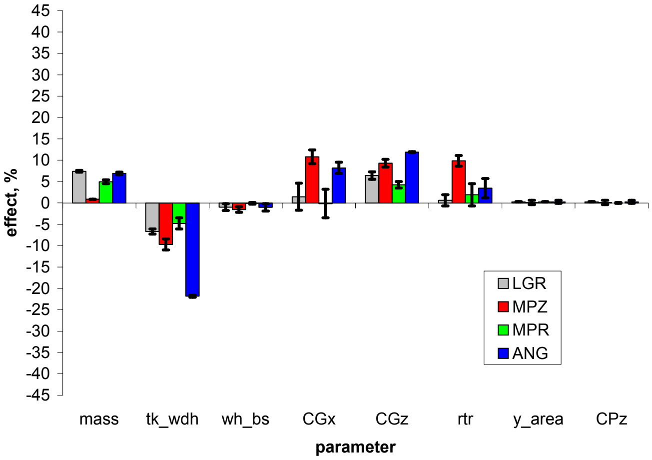

Figure 14. Effect of 20% changes in single parameter values for 10 tonne helicopter

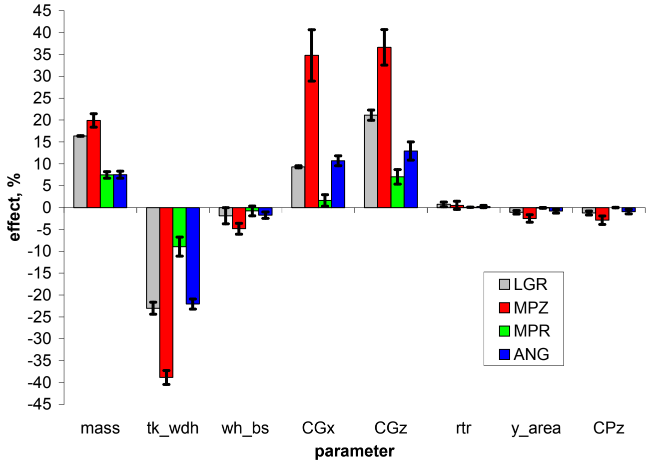

Figure 15. Effect of 20% changes in single parameter values for 15 tonne helicopter

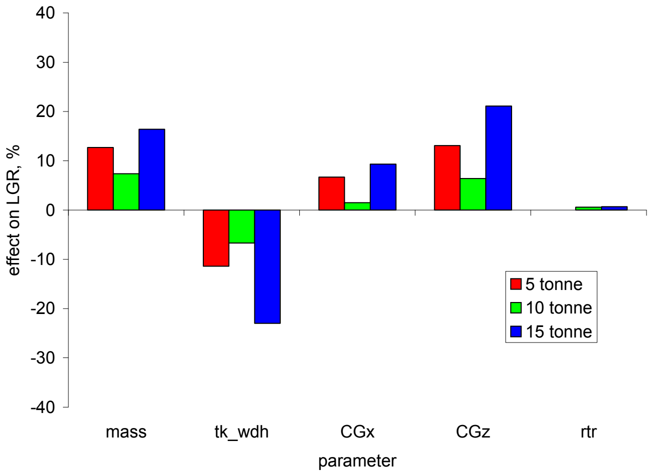

Figure 16. Comparison of landing gear reaction sensitivity to 20% increases in significant parameter values

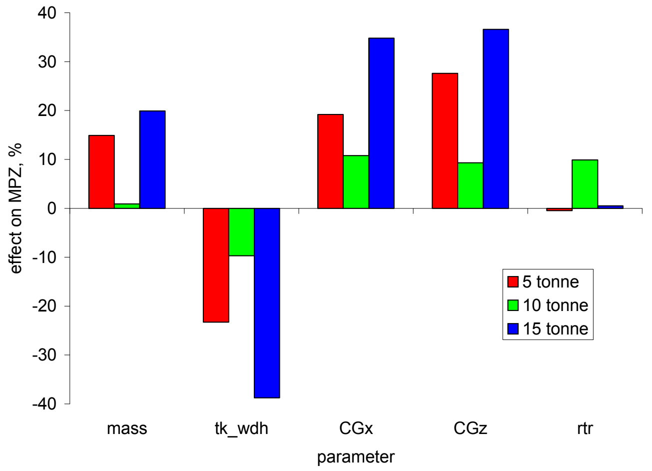

Figure 17. Comparison of vertical securing force sensitivity to 20% increases in significant parameter values

Inspection of the complete set of results shows that only single parameters and few combinations of two parameters have effects greater than the standard errors. Figure 20 shows the absolute value of the sensitivities of individual effects and combinations of two effects for the acceleration case and the 10 tonne aircraft. In this plot it is evident that all sensitivities to combinations of two parameters are not. This generalization applies to all similar results with the exception of three combinations of two parameters that yielded sensitivities that were marginally above the standard error values. Due to marginal significance, these cases are not considered further. The effects of all combinations of more than two parameters are negligible.

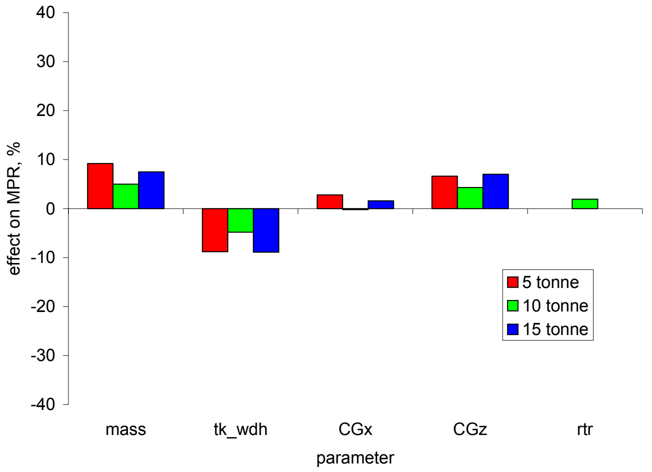

Figure 18. Comparison of radial securing force sensitivity to 20% increases in significant parameter values

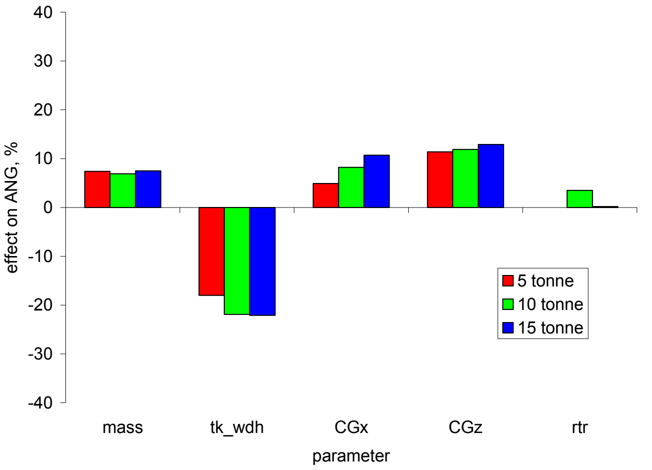

Figure 19. Comparison of aircraft relative angle sensitivity to 20% increases in significant parameter values

DISCUSSION AND CONCLUSION

The study presented in this paper investigated the effect of eight helicopter configuration parameters on shipboard securing requirements for three tricycle-type aircraft of significantly different sizes. Typical aircraft in the 5 tonne, 10 tonne, and 15 tonne weight categories were considered. The specific aircraft configurations were described in terms of numerous nondimensional and dimensional parameters in Table 1, Table 2, and Figure 5. The study did not attempt to show the variation of the magnitude of securing requirements with helicopter size, but rather the variation of sensitivity to various parameters with size. Overall, combining proven dynamic interface analysis methodology and corresponding transient-dynamic simulation with a full-factorial experimental design provided a powerful method for performing analysis of this type.

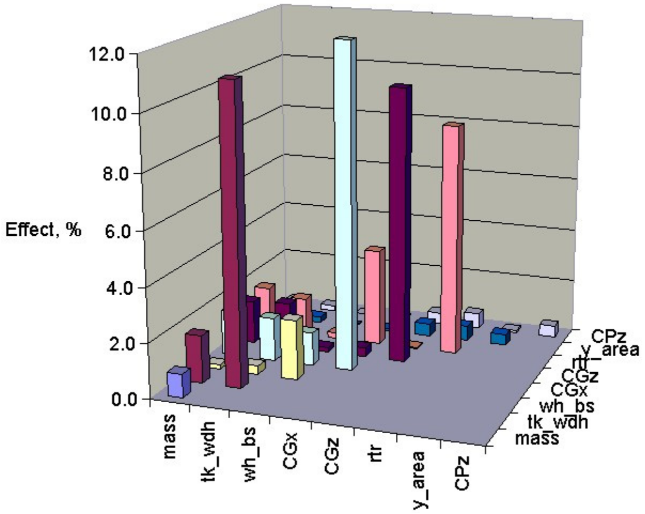

Figure 20. Sample result for two-parameter securing force sensitivities (vertical securing force for peak acceleration ratio case corresponding to the 10 tonne aircraft)

Two interpretations of results were considered. One provided the specific sensitivities of vertical landing gear reaction force, vertical securing force, radial securing force, and aircraft relative angle to the eight specific parameters considered. The second provided comparisons of sensitivities with aircraft size. Specific conclusions are enumerated below.

1. Securing requirements were found to be generally dependent on parametric changes in helicopter configuration.

2. Sensitivity results were found to be relatively independent of the ship motion case considered.

3. Specific mean sensitivity results for each of the three aircraft considered were presented in Table 4 through Table 6 respectively. Readers are referred to the appropriate tables for specific numerical results.

4. The mass, track width, longitudinal position of the centre of mass, and vertical position of the centre of mass were found to significantly affect securing requirements. Wheelbase, projected side area, and centre of pressure height had little effect. The sensitivity to induced rotor loads was found to be much more pronounced for the 10 tonne aircraft than the other two aircraft considered for which the sensitivities were below the established threshold levels on significance. Graphical comparison of significant sensitivities was presented in Figure 16 through Figure 19.

5. Increases in mass and inertial properties, forward centre of gravity location, and vertical centre of gravity location were found to adversely affect securing requirements whereas increases in track width had a very favourable effect on securing requirements.

6. Significant effects were limited to single parameter values with combinations of parameters having negligible effect.

7. The sensitivity of the relative angle was found to remain constant irrespective of aircraft size for the mass, track width, and height of the centre of gravity parameters. The sensitivity to the forward centre of gravity position linearly increased with aircraft size.

8. The sensitivity of the radial probe force was dependent on aircraft basic configuration but did not show a trend with aircraft size for the significant parameters considered. The 10 tonne aircraft showed generally much lower sensitivities than either of the other two.

9. The landing gear reaction force sensitivities showed evidence of being aircraft specific but also showed significantly higher values for the 15 tonne aircraft.

10. The vertical securing requirement sensitivity was aircraft specific but was also significantly higher for the 15 tonne aircraft.

11. In general, vertical probe force is most sensitive to changes in aircraft configuration, followed in decreasing order of magnitude by landing gear reaction force, relative angle, and radial probe force. The ranking of the latter three would change if attention was focussed on a single parameter.

Future work will build on the developed methodology to further quantify the effect of helicopter configuration on shipboard securing performance. Ultimately this research may provide guidance toward the design of helicopters for embarked operation and correspondingly improve the safety of the on-deck operation.

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