AIRFRAME WATER IMPACT ANALYSIS USING A COMBINED MSC/DYTRAN – DRI/KRASH APPROACH

Gil Wittlin
Dynamic Response, Inc., Sherman Oaks, California

Michael Smith
Ashish Sareen, Ph.D.
Bell Helicopter Textron, Inc., Fort Worth, Texas

Marv Richards
Simula Government Products, Inc., Phoenix, Arizona

ABSTRACT

This paper describes a Naval Air Warfare Center (NAWC) sponsored Small Business Innovation Research (SBIR) Phase I Program to achieve long-range U.S. Navy water impact design objectives. In this program, a complementary approach utilizing both a nonlinear finite-element analysis program (MSC/DYTRAN) and a hybrid impact analysis code (DRI/ KRASH) is used to demonstrate the potential for airframe water impact analysis. Several water impact conditions were analyzed comprising various combinations of forward velocity and sink speed using MSC/DYTRAN and DRI/KRASH. Sampling of results along with test data are provided with regard to fuselage underside pressure contours, floor accelerations, airframe-water interactive forces, response comparisons and trends. No similar results have previously been presented.

INTRODUCTION

The U. S. Navy is concerned about the crash safety of their rotorcraft during water impacts as evidenced by the following:

- The U.S. Navy has experienced a high frequency of occurrence of rotary-wing water impacts.
- Experience has shown that during severe but survivable water impacts, dynamic pressures can be significantly higher than the static design requirements.
- The structural response and load transfer mechanism for impacts on water or soft soil is very different than for impacts on hard surfaces.

With a fleet of approximately 1,500 helicopters, all of which perform over water, and for some in which water impacts represent nearly 90% of their accidents (Ref. 1), there is need on the U.S. Navy's part to improve safety during water impact accidents. When compared to research conducted by the U.S. Army, NASA, and the FAA on airframe behavior during hard surface impacts, little water impact research has been done in recent times. Other than minimal ditching requirements, the U.S. Navy has no identifiable water impact design criteria and no acceptable water impact methodology with which to address the water impact scenarios.

As a result, the NAWC sponsored a Phase I SBIR with the following long-range objectives:

- Develop a viable validated methodology with which to evaluate rotary-wing aircraft structural performance in severe but survivable water impacts.
- Establish crash design criteria that will ensure a level of safety consistent with potentially survivable water impact scenarios.
- Consider potential design concepts that will enhance airframe resistance to water impacts.

The principle SBIR Phase I goals for this effort were defined as follows:

- Utilize existing computer simulation programs to predict water impact response parameters such as pressure, force, acceleration time-histories, and the kinematic response of rotary-wing airframes penetrating into water for a range of typical impact conditions.
- Determine the capabilities of the proposed methodology based on available accident data, test data, and analysis, and the existing criteria, both civil and military.
- Demonstrate the technical merit and feasibility of the methodology to accurately represent helicopter airframe behavior for water impact scenarios and survivable envelopes.

Presented at the American Helicopter Society 53rd Annual Forum, Virginia Beach, Virginia, April 29 – May 1, 1997.

METHODOLOGY OVERVIEW

The approach adopted to meet the long-range goals of the U.S. Navy is to use two types of models: hybrid (intermediate) and finite element (detailed). The hybrid terminology refers to the ability to use available test or other data as input along with internal calculation of structural parameters. A pure finite-element model (FEM) program generally does not allow the user to input external test data as an alternative to an internal calculation of such data. These two concepts offer different advantages and disadvantages with regard to achieving the ultimate U.S. Navy goals. The FEM approach offers the following advantages and disadvantages:

FEM Advantages

- Detail design and design condition orientation
- Local interaction/attachment behavior
- Design accuracy
- Specific component application

FEM Disadvantages

- Time-intensive setup and run times
- Does not accept test/other data as input
- Difficult to approximate behavior
- Limited aircraft application/impact scenarios

On the other hand, the hybrid modeling approach has the following advantages and disadvantages:

Hybrid Advantages

- Model setup and fast run times
- Global analysis oriented
- Accepts test and/other data as input
- Preliminary design tool and overall behavior
- Defines critical parameters and conditions
- System application versatility

Hybrid Disadvantages

- Approximate solutions
- Not detail element oriented
- Limited internal criteria
- Not stress-strain oriented
- Not local behavior oriented
- Not component design oriented

The approach presented in this paper utilizes computer codes that provide the greatest opportunity to achieve the stated U.S. Navy goals. Since neither of the available hybrid nor the pure FEM codes have demonstrated a capability to meet all the requirements stated earlier, the combination of FEM/hybrid modeling will, in the long run, be the most advantageous.

The use of both FEM and hybrid analyses as illustrated in Fig. 1 provides for the ability to perform complementary procedures, thus maximizing the strengths of each approach, while minimizing the weakness of each. The FEM offers detailed design analysis potential, particularly for local regions or airframe segments. The hybrid modeling offers a more practical cost-efficient and versatile analysis technique more closely associated with preliminary design, global analysis, and parametric tradeoff studies.

A number of nonlinear, transient dynamic analysis programs can fit into the detailed finite-element concept. Some

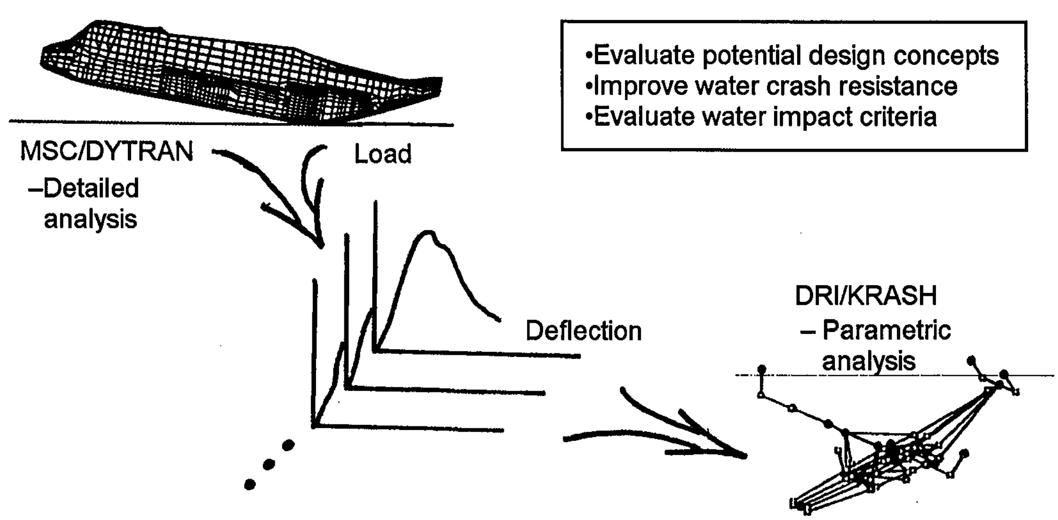

Fig. 1. Combined FEM/hybrid approach.

are available as public domain programs (e.g., DYNA3D), while others are commercially available (e.g., MSC/DYTRAN). The choice of available hybrid programs is more limited. The most prominent hybrid code is KRASH which was initially developed under U.S. Army sponsorship and subsequently under FAA sponsorship. The most widely used public domain version is KRASH85. Since 1991, Dynamic Response, Inc. (DRI) has provided a commercial version of KRASH with enhanced features.

Since the SBIR Phase I effort does not allow a detailed assessment of all codes, MSC/DYTRAN and DRI/KRASH were chosen as the representative state-of-the-art detailed and hybrid codes, respectively, to prove concept feasibility.

Description of MSC/DYTRAN

MSC/DYTRAN† is a general-purpose finite-element code that uses the explicit formulation of the finite-element method to treat significant nonlinear problems with geometric and material nonlinearity. It contains both Lagrangian and Eulerian processors. The Lagrangian processor uses a control mass approach and is primarily applicable to structural problems. The Eulerian processor uses a control volume approach and is used mainly for fluid problems. The two processors can be coupled in two different ways (ALE and general coupling), depending on the nature of the problem.

The MSC/DYTRAN structural model can be made up of isotropic or orthotropic shell and/or solid elements with elastic-plastic yield/failure criteria or composite failure models. It is possible in MSC/DYTRAN to model the structure as Lagrangian and have it surrounded by an Eulerian mesh. The space above the water can be filled with a void or with air. It is also possible to model the fluid with Lagrangian solid elements having no yield strength. Depending on the objectives of the model, each approach contains advantages and disadvantages. Thus, as with any methodology, the user's understanding of the code's strengths and weaknesses and user's experience is essential.

Description of DRI/KRASH

The DRI/KRASH code evolved from the KRASH public domain version. Ref. 2 contains a description of KRASH features and applications and is representative of the numerous KRASH-related publications. Some of the DRI/KRASH features that are not available in the public domain KRASH are summarized as follows:

†MSC/DYTRAN is a registered trademark of the MacNeal-Schwendler Corporation, Los Angeles, California.

- PC and workstation portability
- Variable integration
- Metric system
- Occupant head strike analysis
- Soft soil module
- Expanded landing gear module
- Beam and terrain property card options
- Water impact module (see Table 1)
- Compatible pre- and post-processing software available

ANALYTICAL APPROACH

The approach to demonstrating feasibility of the methodology is as follows:

- Using MSC/DYTRAN, model an aircraft for which scale-model test data exists for a series of impact scenarios. Select impact conditions for the express purpose of (1) being in a survivable water impact range, (2) providing realistic impact response data, (3) covering a range of diverse impact conditions and modeling options, and (4) distinguishing the effect of selected parameters, e.g., velocity components, aircraft

Table 1. DRI/KRASH hydrodynamic features

Modeling Surfaces	Lifting, drag, and vertical penetration surfaces 100 primary and secondary lifting and drag surfaces Multiple point attachments to drag surfaces Design and failure load criteria Multiple shape provisions - lifting and penetration surfaces Sphere, cone, horizontal and vertical cylinder, conical, spherical, and parabolic nose shapes
Sea State	Wave height and length, wind magnitude and direction Face landing; up-slope and down-slope, parallel landing Crest, trough, and wave propagation
Load-Deflection Option	Structure coupling ; contact surface deformation, energy dissipation, force, deflection and energy plots
Surface Plots	Penetration, force, and pressure
Factors	Scale for shape, fem data, test data
Element Library	Provisions for standard hydrodynamic data
Overall RMS Pressure	Standard calculation for reference

attitude, and airframe deformability, on the response characteristics.

- From the MSC/DYTRAN modeling effort, obtain acceleration, pressure, and deflection responses both at the aircraft CG and at selected fuselage stations for which comparable scale model test data is available. Provide this data to KRASH in the form of pressure time-histories, peak responses, and force-deflection curves.

- Create DRI/KRASH model(s) representative of the scale model ditching condition(s) that are analyzed with MSC/DYTRAN. Modify the KRASH model, as appropriate, with test or detailed FEM analysis data, and exercise the DRI/KRASH options to perform water impact analyses.

- Perform a series of parametric studies utilizing existing rotary-wing DRI/KRASH hybrid models to demonstrate the wide application of the hybrid approach. Two rotorcraft, one at 9,000 lb GW and the other at 20,000 lb GW, discussed in References 3 and 4 provide two distinct accident scenarios and two distinct aircraft configurations, including gear-extended and gear-retracted situations.

MSC/DYTRAN Analyses

The objectives of the MSC/DYTRAN analyses are to (1) demonstrate capability with regard to many of the methodology requirements, and (2) to provide data that can be utilized in hybrid analysis to complete the tasks of a comprehensive methodology. To meet these objectives, ten water impact conditions listed in Table 2 were analyzed.

Since water impact test data was available from Ref. 5 for a

Table 2. Water impact conditions analyzed using MSC/DYTRAN

Case No.	Sink rate (ft/sec)	Forward velocity (kn)	Pitch (degrees)	Fuselage type
Lagrangian Water Mesh				
1	6	30	+10	Rigid
2	24	30	+10	Rigid
3	6	60	+10	Rigid
4	24	30	+10	Deformable
5	24	0	0	Rigid
6	24	0	+10	Rigid
Eulerian Water Mesh				
1	6	30	+10	Rigid
2	24	30	+10	Rigid
3	6	55	+10	Rigid
4	6	0	+10	Rigid

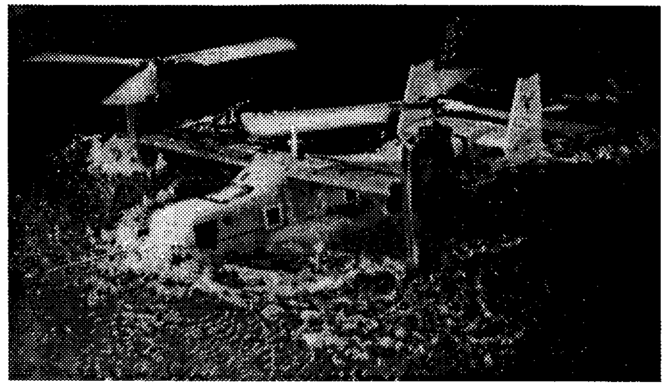

Fig. 2. Scale model water impact test.

scale model of a tiltrotor at 42,600 lb GW (Fig. 2), this configuration was selected for water impact analysis under calm sea-state conditions. The fuselage of the aircraft was modeled with MSC/DYTRAN using 2,977 rigid planar elements as shown in Fig. 3. The wing and nacelles were not represented since test data indicated the peak pressures and accelerations occurred while the aircraft is still in a nose-up pitched attitude and thus prior to water contact with the nacelles.

The fluid was modeled initially using 43,200 Lagrangian solid elements with no yield strength that covered an area of 600 inches long by 300 inches wide and 240 inches deep. Since, for the condition analyzed, the aircraft had no yaw or roll attitude and rate, a symmetric half model of the Lagrangian mesh was used to reduce the computation time. Modeling fluids with Lagrangian solid elements significantly reduces the computational time required by simplifying calculations for fluid-structure interaction; however, Lagrangian elements lose some physical fidelity available with Euler elements. In addition, the Lagrangian mesh length of 600 inches proved to be inadequate to capture the full sequence of water impact. Furthermore, contour mapping of fuselage underside pressures is currently available only for Eulerian meshes. Therefore, subsequent modeling used 32,400 Eulerian elements to represent the water and 10,800 Eulerian elements to model the air above the water mesh. The total Eulerian mesh covered an area of 1,200 inches long by 600 inches wide and 100 inches deep. The

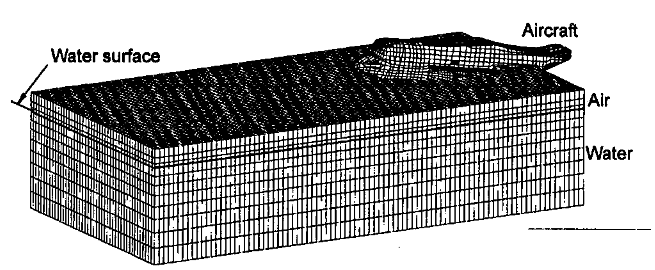

Fig. 3. MSC/DYTRAN model of aircraft and fluid

fluid mesh in the area of initial impact had elements each with a size of 13 inches long by 13 inches wide and 10 inches deep. The Eulerian air mesh up to 3 ft. height above the water surface was used to maintain general coupling between the Lagrangian fuselage and the Eulerian water after rebound and secondary recontact.

The results of the MSC/DYTRAN analysis at 30 kn forward velocity, 6 ft/sec sink rate, 67-percent rotor lift and 10-degree nose-up attitude using the Eulerian fluid mesh (Fig. 4) show the aircraft reaching a nearly level attitude at a p-proximately 0.50 seconds which is consistent with the re-ported test results. Initial impact at time 0.005 seconds resulted in a peak pressure of 21.0 psig at fuselage station (FS) 550. At time 0.025 seconds, a peak fluid pressure of 22.0 psig is noted in the analysis at FS 535.5 as shown in Fig. 5 (versus approximately 23.1 psig measured in test at FS 532). Thereafter, the peak fluid pressure continues to decline to approximately 4 to 6 psig as the aircraft levels off.

At the aircraft CG, the analysis indicates a peak vertical deceleration of 2.5 *g* was reached as shown in Fig. 6 (versus test results of 1.9 *g* at FS 412 near the CG). Correspondingly, the longitudinal deceleration peaks at 0.35 *g* as shown in Figure 6 (versus 0.7 *g* measured in test). The corresponding reduction in vertical and longitudinal velocity at the fuselage CG is shown in Fig. 7. As the aircraft sinks

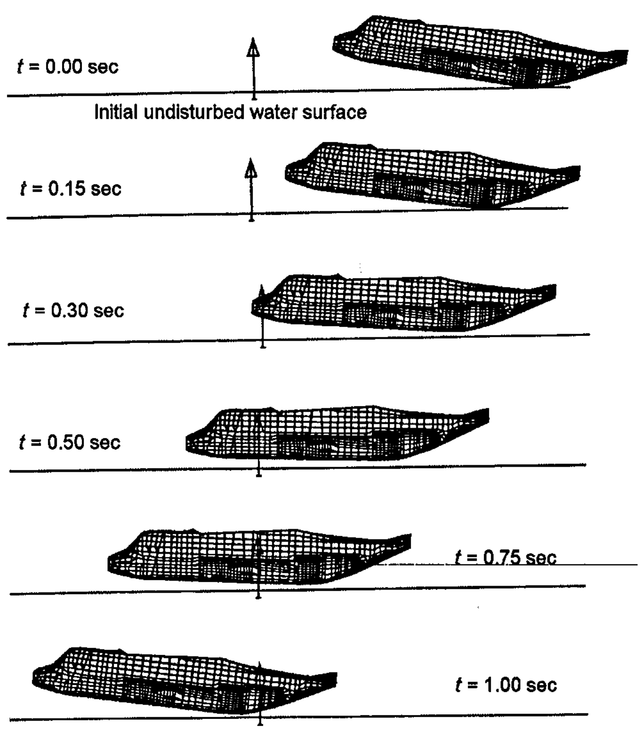

Fig. 4. MSC/DYTRAN simulation of water impact.

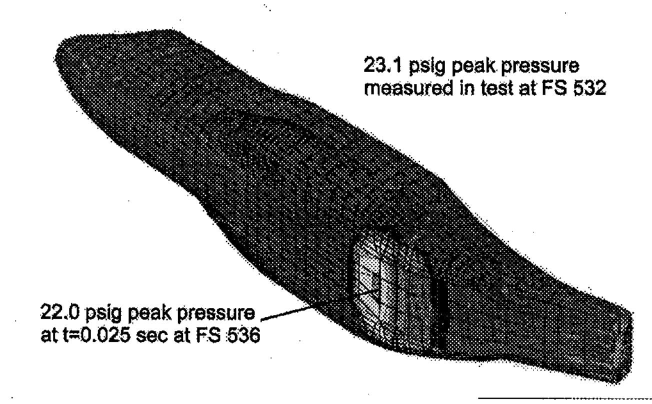

Fig. 5. Impact pressure for ditching for 30 kn forward velocity and 6 ft/sec sink rate.

into the water and drags forward, the nose down (negative) pitching moment of the aircraft CG continues to increase until the aircraft starts to level off and areas ahead of FS 550 and longitudinally closer to the aircraft CG impact the water at approximately 0.50 seconds.

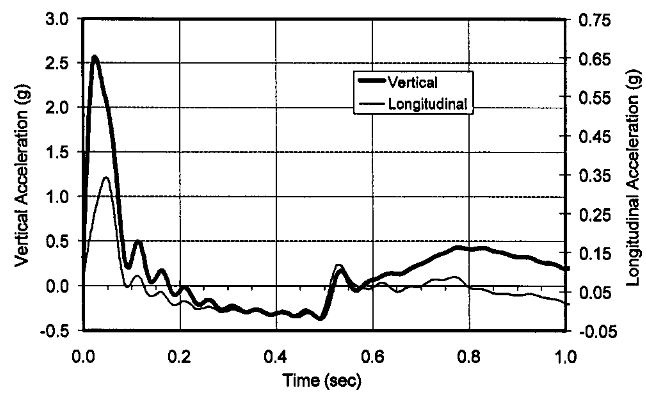

Fig. 6. Acceleration time history at fuselage CG for 30 kn forward velocity and 6 ft/sec sink rate

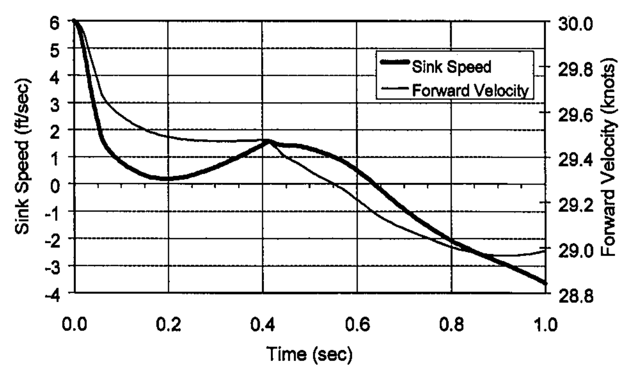

Fig. 7. Aircraft CG velocity time history for 30 kn forward velocity and 6 ft/sec sink rate.

Analyses were also performed with the Lagrangian aircraft structure coupled with the Eulerian fluid mesh to investigate other parameters.

Effect of Sink Rate. The Eulerian analysis with a rigid Lagrangian airframe showed that increasing the sink speed from 6 ft/sec to 24 ft/sec resulted in the following:

- FS 550 pressure at $t = 0.005$ sec increases from 18.2 psig to 350 psig.
- FS 512 pressure at $t = 0.100$ sec increases from 22.8 psig to 353 psig.
- CG vertical acceleration increases from 2.5 *g* at 0.055 second to 20 *g* peak at $t = 0.008$ sec.
- CG longitudinal acceleration increases from 0.35 *g* at 0.085 second to 2.0 *g* peak at $t = 0.010$ sec.

Acceleration data was estimated to show increases of factors between 5 and 10 for the longitudinal and vertical directions, respectively. There is no comparable scale test data for acceleration versus sink speed at a particular forward velocity. A four-fold increase in sink speed could have a significant effect on the vertical acceleration, particularly if the forward velocity does not contribute to the vertical pulse. While not a direct comparison, a pure vertical impact in which the sink speed increases four-fold could result in an six-fold increase in acceleration based on the hybrid analysis of a severe sink speed accident. Since that analysis was based on spherical shapes, flatter contours such as those associated with the scale model test article could produce higher responses, which means that a ten-fold increase, while high, is possible for non-deformable subfloor structures.

The analysis shows that the maximum pressure increases by a factor of approximately 19 at $t = 0.005$ sec and by a factor of 15 at $t = 0.100$ sec. These impact pressure increases are consistent with the factor associated with the velocity squared term associated with the four-fold increase in sink speed from 6 to 24 ft/sec.

Lagrangian analysis, which provides forces rather than pressures and thereby allows panel load-deflection relationships to be developed for KRASH, shows that the four-fold sink speed increase results in a 14-fold increase in peak vertical CG acceleration and approximately an eight-fold increase in peak fuselage underside panel forces.

Effect of Forward Velocity and Other Factors. Other pressure and acceleration comparisons were made to understand the

- Effect of forward velocity at a specified sink speed.
- Effect of impact attitude at a given sink speed and no forward velocity effect.
- Effect of forward velocity for a given sink speed of 6 ft/sec.
- Effect of deformable versus rigid representation.

In general, the trends exhibited by the analyses are realistic. However, quantitative verification of such trends is sometimes difficult to assess due to the lack of available test data. This is illustrated in Table 3 which compares the analytically determined trends with available test data for the effect of forward velocity.

Effect of Different Fluid Modeling. The FEM analyses demonstrated differences in results between using Eulerian and Lagrangian meshes to model the water. Some of the tradeoffs between modeling the water with an Eulerian versus a Lagrangian mesh can be summarized as follows.

The Eulerian mesh provides for the treatment of the interaction forces as fluid-structure coupling. MSC/DYTRAN determines which fluid elements are intersected by which structure elements and then applies forces to the face of each element based on the pressure in the intersected fluid elements. Thus, it is simpler to recover pressures than forces and makes pressure-mapping onto the airframe contour feasible. This method allows the water to flow freely through the fixed (or deformable) mesh which may be more appropriate for higher sink rate cases. With this type of mesh the program is required to perform a large number of three-dimensional geometric intersection calculations at each time step. These calculations determine (1) how much of each Euler element at the boundary is covered by structure to compute flow into and out of those cells, and (2) which Euler and Lagrangian elements intersect and what is their relative intersected areas in order to compute the forces felt by the structural element. These calculations are CPU intensive. While techniques exist within MSC/DYTRAN to reduce this CPU time, the tradeoff is accuracy.

Table 3. Effect of increase in forward velocity
(Ratio of 55 to 30 kn Forward Velocity)

	MSC/DYTRAN Lagrangian Mesh Results	Scale model Test Data (Ref. 4)	Other Test Data (Ref. 5)
Vertical Acceleration Factor	1.20	1.5	2.0 *(a)*
Pressure/Forc eFactor	1.13	1.5-1.7 *(b)*	N/A

(a) 100 to 150 kn forward velocity
(b) 20 to 30 kn forward velocity

By contrast, the Lagrangian mesh provides for the treatment of interaction forces as structure-structure contact, and the contact forces are applied to the grid points of both meshes at the point of contact. Thus, it is simpler to recover forces, but difficult to compute pressures. The extreme deformation of the water mesh may hinder high sink rate cases. This type of mesh allows for a definition of aircraft-water contact in multiple regions with each region corresponding to a section of aircraft equivalent to that used in the DRI/KRASH model of the aircraft, thus allowing direct recovery of force-time histories at specific locations and easy computation of force-deflection curves at these locations. Pressure mapping is not feasible with this approach because the Lagrangian processor provides only point forces.

While depicting ditching behavior and trends reasonably well, the FEM modeling results can be refined and improved with regard to high sink speed and deformable structure representations. Furthermore, modeling techniques with regard to mesh size, coupling (Eulerian) versus contact (Lagrangian) surface, the effect of the use of voids, air gaps and reflective surfaces (e.g., walls, flow boundaries) can be also be improved.

The computational expense for modeling, run-time, and post-processing can be substantial, depending on the size and type of the structure and the impact simulation. The run times for 0.50-second simulations of ditching impact conditions with rigid structure models varied from 2.5 to 5 hours, depending on the work station used. Deformable structure models required an order of magnitude more run time for comparable simulation times.

DRI/KRASH Analyses

DRI/KRASH hybrid modeling used currently available KRASH models of a 9,000 lb, a 20,000 lb rotorcraft, and a 42,600 lb VTOL aircraft. Each model was modified to accommodate the hybrid modeling requirements for representing hydrodynamic forces. The objective of these analyses are to demonstrate the advantages of the hybrid approach, i.e., (1) analysis of the entire impact scenario (beyond initial impact), which is not well suited for detailed FEM, (2) versatility of application to different aircraft configurations and a wide range of impact conditions, and (3) utilization of available test or FEM data.

For the purpose of subsequent discussion, the DRI/KRASH hybrid models are designated as follows:

TYPE 1 - 9,000 lb rotorcraft
TYPE 2 - 20,000 lb rotorcraft
TYPE 3 - 42,600 lb VTOL aircraft.

The DRI/KRASH models are shown in Fig. 8. The respective model sizes, simulation times and computer runtimes are noted in Table 4.

The Type 1 model simulation is representative of a rotorcraft accident with gear extended and a high forward velocity (169 ft/sec), low sink speed (5 ft/sec), nose-up (+3-degree) impact attitude, which has demonstrated reasonable results when compared to the available accident data. Simulating this condition, which resulted in severe damage

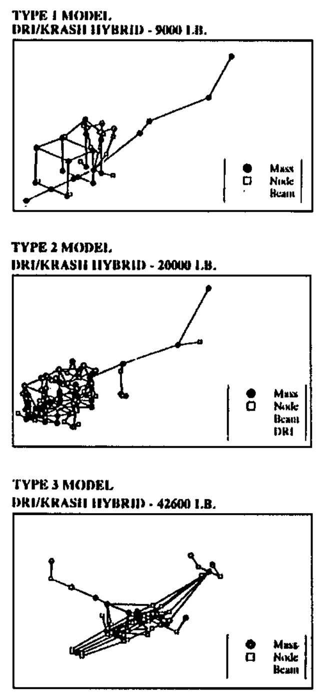

Figure 8. DRI/KRASH hybrid models.

Table 4. Hybrid model sizes

Parameter Numbers *(a)*	TYPE 1	TYPE 2	TYPE 3
Masses	24	68	21
Beams	32	116	38
Node Points	14	40	34
Hydrodynamic Lift Surfaces	8	24	6
Hydrodynamic Drag Surfaces	8	24	6
DRI's *(b)*	0	4	0
Simulation Time (sec)	0.120	0.200	0.500
Computer CPU runtime *(c)*	1.64	10.0	4.5

(a) Full Model
(b) Dynamic Response Index Spinal Injury Elements
(c) Minutes - Pentium 120 MHz PC

Table 5. Type I hybrid model impact conditions.

Case Number	1	2	3	4	5	6	7	8	9	10
Forward Velocity (ft/sec)	169	72	72	122	122	122	122	122	122	72
Failure Criteria (psi)	12	12	12	12	12	100	100	100	12	12
Radius (in.)	20	20	20	20	100	100	100	100	20	20
Miscellaneous	*(a)*		*(b)*				*(c)*	*(d)*	*(e)*	*(f)*

Unless noted otherwise, all cases are: sink speed = 6 ft/sec, 3-degree nose-up pitch, 0-degree yaw, 0-degree roll, symmetric impact, calm sea, 1-*g* Lift, and LG extended. Forward velocity, fuselage underside spherical radius, and failure design criteria for fuselage underside panels are listed for each case and miscellaneous changes are also noted.

(a) 5-ft/sec Sink Speed
(b) No Lift
(c) Parallel-to-Crest landing
(d) Perpendicular to crest landing
(e) Unsymmetrical: 10-degree roll, 10-degree yaw
(f) Landing gear retracted

and nose-over behavior, allows the engineer to evaluate a number of possible design changes or operational variations. Table 5 shows the impact conditions analyzed for the Type 1 model.

The Type 2 model simulation is representative of a severe 50 ft/sec sink speed, 10-degree nose-down pitch accident in which extensive airframe damage and fatalities occurred. Analysis of this condition enables the engineer to evaluate the effect upon occupant survivability that selected design changes or operational procedures could have. Table 6 shows the impact conditions analyzed for the Type 2 model.

The Type 3 model simulation is representative of a ditching test configuration with impact conditions representative of current ditching design criteria and well within the survi v-able impact envelope.

A discussion of hybrid analyses results for DRI/KRASH hybrid model follows.

Type 1 Hybrid Model – Calm Versus Sea State Landings. Ditching into calm sea (Case 6, Table 5) was compared to landings into a sea with a wave length of 60 ft, and a wave height of 4 ft (length to height ratio=15). Landings parallel to a wave crest (Case 7) and perpendicular to a wave crest (Case 8) were analyzed. For a forward velocity of 122 ft/sec, acceleration levels at the aircraft CG for these three conditions are noted below:

Case No.	Landing Condition	Longitudinal Acceleration (*g*)	Vertical Acceleration (*g*)
6	Calm Sea	6.4	2.0
7	Parallel To Crest	6.6	2.9
8	Perpendicular to Crest	13.7	6.8

Table 6. Type 2 hybrid model impact conditions.

Case Number	1	2	3	4	5	6	7	8	9	10
Sink Speed (ft/sec)	50	40	40	40	40	30	24	40	24	24
Underside radius	200	200	100	50	100	100	100	100	100	100
Pitch Attitude (degrees)	-10	-10	-10	-10	-10	-10	-10	+10	+10	+10
Miscellaneous					*(a)*					*(b)*

Unless noted, all cases include: linear seats, 100 psi underside panel design criteria, a symmetrical impact and a spherical representation of underside panel surface. Sink speed and pitch attitude at impact, and panel underside radius for each case is listed. Miscellaneous changes are noted.

(a) Load Limiting 12-inch stroking seat
(b) 30 kn (50 ft/sec) Forward Velocity

Based on the above DRI/KRASH analysis results and data in Fig. 9, the most severe condition is landing perpendicular to the wave crests. Landing parallel to the wave crest provides results very close to that of a calm sea. Aircraft ditching manuals and FAR-AIM advise that if at all possible during an emergency landing on water, landing parallel to the wave crest is more desirable than landing into the wave. These results are consistent with that recommendation.

Type 2 Hybrid Model Analysis – Injury Potential. DRI/KRASH analyses were performed to investigate the effect of a stroking seat on the potential for occupant spinal injury. The results of these analyses, performed for the same sink speed (40 ft/sec) and underside contour surface (100 inches radius) are noted as follows:

Case No.	Condition	Vertical Acceleration At Floor (g)	Peak DRI Value
3	No Stroke	31.0	34.2
5	12-in. Stroke	33.2	13.0

The analytical results (Case 3, Table 6) show that the resulting floor loads are sufficiently high to cause occupant spinal injury (DRI > 18). The analysis with a 12-inch stroking seat shows that, while the floor loads remain high, the stroking seat can reduce the occupant loads to a non-injurious DRI level of 13. Fig. 10 depicts the analytically obtained DRI time history for each of these cases. In the accident from which this analysis evolves (Case 1) there was support structure failure, negating the benefit of a stroking seat. More detailed FEM analysis of the airframe/seat interaction or extension of the hybrid analysis to institute its secondary water impact surfaces capability at the floor structure would allow for an assessment of that potential failure mechanism.

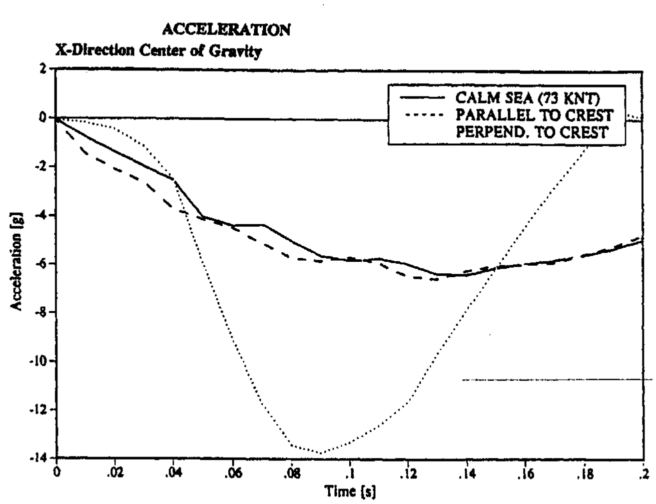

Figure 9. Effect of sea state on longitudinal acceleration.

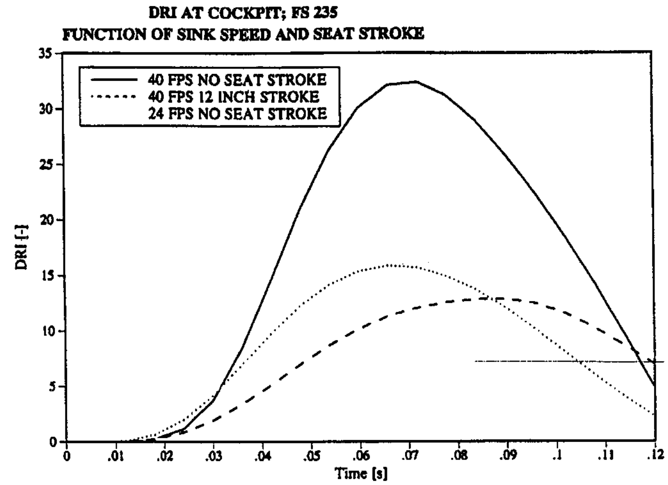

Fig. 10. DRI time history for different impact velocities.

Other analyses for Type 1 and Type 2 models indicated agreement with anticipated trends but are not discussed herein. These include

- The effect of landing gears extended versus retracted.
- The effect of sink speed on underside pressures.
- The effect of fuselage underside contour on accelerations and pressures.
- The effect of pitch attitude, unsymmetrical impact conditions and design criteria on aircraft response.

Type 3 Hybrid Model Analysis – Ditching Condition Analysis. The DRI/KRASH hybrid analysis was performed for the 42,600 lb aircraft for the same ditching conditions as noted earlier for the MSC/DYTRAN analysis. The results for the forward CG case, shown in Figs. 11 through 13, indicate the following:

- The peak responses (see Table 7) occur within 0.080 seconds after impact and are between 2.3 *g* (analysis) and 2.6 *g* (test) at the aft end, 1.3 *g* and 2.5 *g* (analysis) versus 1.9 *g* (test) at the mid fuselage and between 1.0 *g* to 2.8 *g* (analysis) versus 1.5 *g* to 1.7 *g* (test) at the forward fuselage.

- The peak longitudinal acceleration is observed in the test to be approximately 0.75 *g* and to occur around 0.090 sec after impact. The peak longitudinal acceleration occurs at around 0.080 sec after impact and varies from 0.52 *g* (at a FS 342 mass) to between 0.9 to 1.0 *g* at locations comparable to where the vertical direction accelerations were measured.

The peak pressures (see Table 8) are in good agreement at the five locations in proximity to the measured locations (Ref. 5).

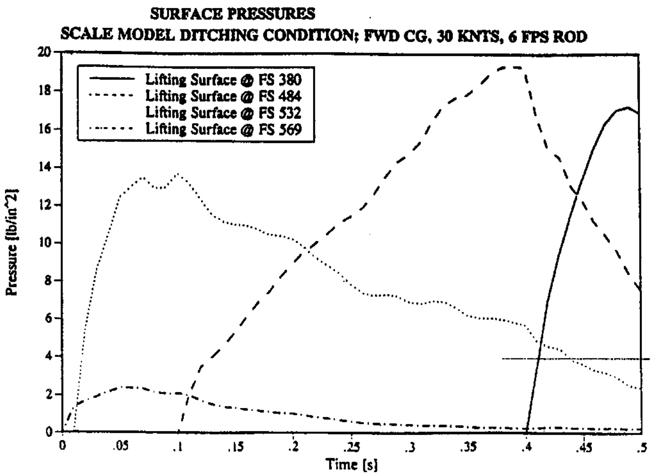

Fig. 11. Pressure time histories for 30 kn forward velocity and 6 ft/sec sink rate.

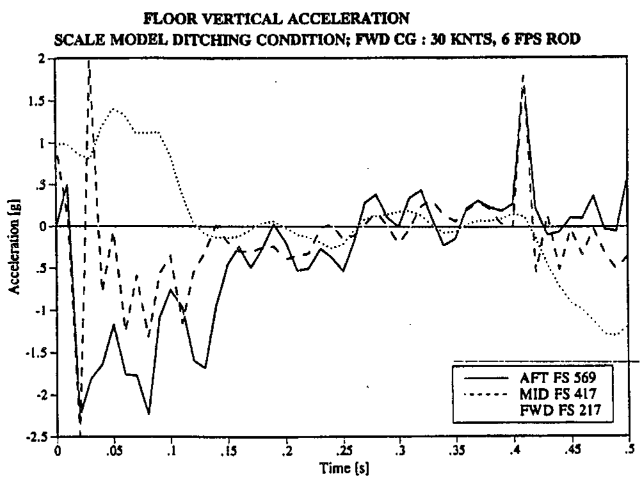

Fig. 12. Floor vertical accelerations for 30 kn forward velocity and 6 ft/sec sink rate.

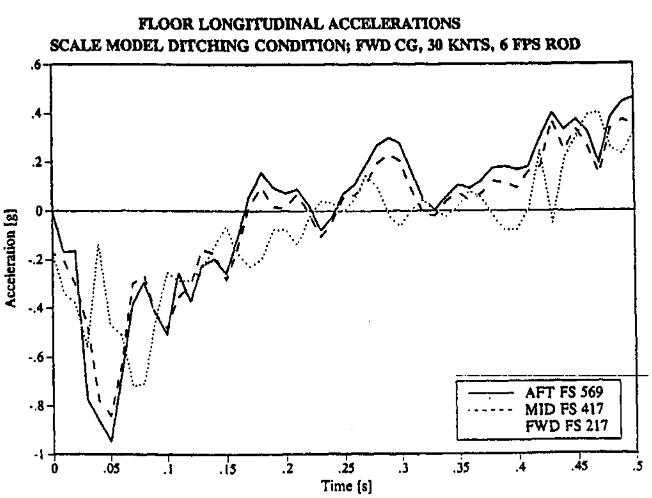

Fig. 13. Floor longitudinal acclerations for 30 kn forward velocity and 6 ft/sec sink rate..

Table 7. Summary of peak accelerations comparisons.

Location	Analysis	Test
Vertical Acceleration – g at time (sec)		
FS 552-576	2.3 (0.020)	2.6 (0.027)
	2.3 (0.020)	2.5 (0.080)
	1.7 (0.120)	1.9 (0.150)
FS 412-417	2.5 (0.020)	1.9 (0.027)
	1.3 (0.080)	1.9 (0.072)
FS 217	1.0 (0.050)	1.5 (0.030)
	1.4 (0.160)	1.6 (0.072)
	2.8 (0.210)	1.7 (0.250)
Longitudinal Acceleration – g at time (sec)		
CG	0.52 (0.080)	0.75 (0.090)

- The analysis pressure pulses are generally broader and the peaks occur later in time than when compared to the test data. This is attributed to the fact that the h y-brid analysis treats contact surfaces as spheres with large radii, when in reality the VTOL aircraft underside panel is flat. A flatter surface tends to produce sharper, higher hydrodynamic forces and pressures.

- The analysis indicates that the aircraft reaches a 1.57-degree nose-up attitude at 0.500 seconds after impact from the initial 10 degree nose-up attitude. At this time, the pitch attitude is still decreasing although at a

Table 8. Summary of peak pressure comparisons.

	Peak pressure-(psi) at time (sec)		Initial contact of FS after impact (sec)	
Location	Analysis	Test	Analysis	Test
FS	2.6 (0.050)	3.0 (0.018)	0.000	0.000
552-576	-	-7.0 (0.072)	-	-
FS 532	16.2 (0.070)	18.0 (0.050)	0.020	0.033
	16.4 (0.100)	-	-	-
FS 486	19.7 (0.390)	20.0 (0.136)	0.110	0.108
FS 380-386	17.2 (0.490)	14.0 (0.430)	0.410	0.380

substantially reduced rate. The test results indicate that the aircraft held attitude at touchdown, then trimmed slowly to a level attitude before settling and slowing down, which supports the sequence of peak pressure readings. The attitude of the aircraft in the analysis also supports the peak pressure sequence and is in agreement with the test data.

Combining MSC/DYTRAN and DRI/KRASH Analyses

From the results of the analyses, several important points can be made about the hybrid analysis and the relationship between the hybrid and FEM analyses.

1. The hybrid analysis produces a hydrodynamic force acting on the surface of the structure. The calculated pressure is based on a force acting over an effective area. While the hybrid code produces forces that are generated by discrete shapes (sphere, cylinder, cone, and combinations of each), it has provisions for altering this force by instituting a "hydrodynamic force factor" and/or by changing the shape geometry, as may be provided by FEM results or test data.

2. The hybrid code does not currently account for negative pressures (suction forces) directly. It does provide for representative time histories of these forces acting at the contact surface as "external forces". Suction forces determined by FEM and/or empirical data can be incorporated into the hybrid model.

3. The hybrid analyses performed in this effort represented the water contact surfaces as rigid links. The alternate option contained in the hybrid code to represent the water contact surface as a compressive spring (linear or nonlinear) was not exercised. This latter a pproach would accept FEM or test data that is presented in the form of load versus deflection.

4. The results from both the hybrid code and FEM code analyses indicate potential for depicting airframe-water interaction behavior, but do need additional refinements and verification. The comparative results provided in Table 9 indicates several areas of both agreement and disagreement between the methodologies and with the tests.

The Technical Merit and Feasibility Assessment

The combined FEM/hybrid methodology to accurately represent helicopter airframe behavior for water impact scenarios and survivable envelopes has been demonstrated to be feasible. The assessment included the following:

Table 9. Summary of analyses and scale model ditching test results, forward CG

	DRI/KRASH	MSC/ DYTRAN	Test Data (Ref. 5)
Pressures-psi at (time-sec)			
FS552-576	-2.0 to + 2.6 (0.050)	--	+3.0 to -7.0 (0.018-.072)
FS532	16.2 to 16.4 (0.070-0.100)	18.2 (0.005)	18-19 (0.050)
FS486	19.7 (0.390)	22.8 (0. 100)	20.0 (0.136)
FS380-386	17.2 (0.490)	--	14.0 (0.430)
Acceleration - *g* at CG			
Vertical	1.3 - 2.5 (0.020-0.080)	2.5 (0.055)	1.9 (0.027-0.072)
Longitudinal	0.5 (0.080)	0.35 (0.085)	0.7 (0.080-0.090)

1. A total of 12 different and distinct impact and ditching test conditions were analyzed with both the FEM and hybrid analyses.

   - These conditions are noted in Fig. 14 along with accident data impact envelopes.
   - These conditions are part of 32 separate analyses reported in the Phase I effort.

2. The 42,600-lb GW rotary-wing aircraft was modeled and analyzed using MSC/DYTRAN for several impact conditions representing:

   - Ditching test conditions that provided data with which to compare analytical results.
   - Impact conditions from which response forces and trends could be obtained.

3. The 42,600-lb GW rotary-wing aircraft was modeled and analyzed using DRI/KRASH for selected impact conditions consistent with the FEM and scale-model ditching tests.

   - Ditching condition with calm sea; forward and aft CG positions.

4. A 9,000-lb GW rotary-wing aircraft was modeled and analyzed using DRI/KRASH for several parametric variations, including the effect on responses and aircraft behavior of:

   - Forward velocity (72, 122, 169 ft/sec)
   - Lift versus no lift

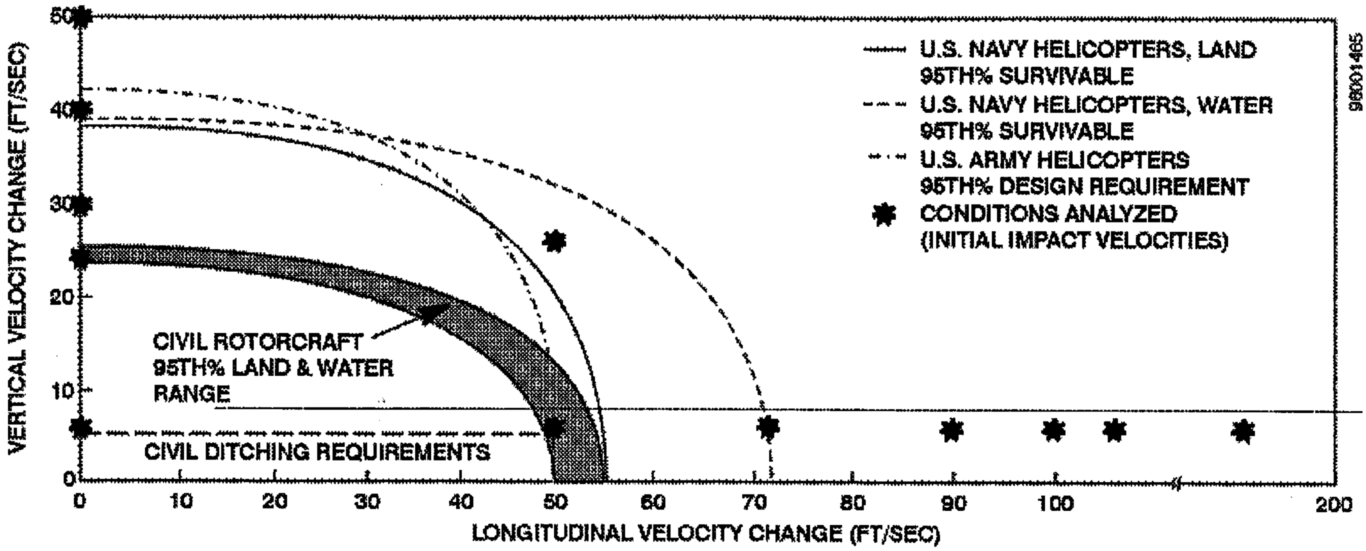

Fig. 14. Design impact conditions and conditions analyzed.

- Impact shape and design criteria.
- Sea state; parallel and perpendicular wave landings.
- Symmetrical versus unsymmetrical landings.
- Landing gear extended versus landing gear retracted.

5. A 20,000-lb GW rotary-wing aircraft was modeled and analyzed using DRI/KRASH for several parameter variations including the effect on responses and airframe behavior of:

- Aircraft underside contour: shape, configuration, and size.
- Energy-absorbing seats on occupant injury potential.
- Sink speed (24, 30, 40, 50 ft/sec).
- Pitch attitude (±10 degree).

The technical merit of this approach is best established by the reasonably good correlation of most fundamental parameters. Kinematic behavior in terms of acceleration and kinetics in terms of pressures trend well with available test data as shown in Tables 3, 7, 8, and 9.

CONCLUSIONS

An analytical approach has been described that can be used to evaluate rotorcraft water impacts. The analytical approach adopted combines an advanced FEM code, MSC/DYTRAN, with a hybrid code, DRI/KRASH. Material contained in this paper is derived from a more extensive study conducted under a U.S. Navy Phase I SBIR Program.

The following can be concluded from the material presented herein.

1. The benefits of each type of analysis, both advanced FEM and hybrid, have been demonstrated and shown to be complementary to the overall evaluation of the impact scenario. The advanced FEM analysis allows detailed evaluation of the impact phenomena and the corresponding local structural response due to the high impact pressures. The hybrid analysis allows analytical simulation of the entire crash scenario beyond the initial impact and rapid evaluation of many different parameters such as the effects of landing gear extended or retracted or the effects of various sea conditions. Discussion is contained in the body of this paper on the potential of utilizing MSC/DYTRAN output as input to DRI/KRASH for a combined evaluation.

2. Reasonable accuracy exists for the lower energy water impacts for which acceleration and pressure data exists (30 kn forward velocity and 6 ft/sec sink rate). For the higher energy water impacts, such as 50 ft/sec rate, the calculated kinematic response of the airframe is consistent with the accident data. This agreement with limited measured and observed data establishes the potential and technical merit of this approach.

3. The potential of the combined FEM/hybrid approach as an analytical tool to support rotorcraft design and assist in the establishment of water impact design criteria has

been pointed out. Case studies presented illustrate the potential for both detailed examination of structural response and evaluation of many different structural, configuration, and impact condition parameters.

REFERENCES

1. Coltman, J., Arndt, S., "The Naval Aircraft Crash Environment; Aircrew Survivability and Aircraft Structural Response," NADC 88108-60, Simula, Inc., Sept. 1988.

2. Wittlin, G., "Program KRASH: The Evolution Of An Analytical Tool To Evaluate Aircraft Structural Response" AHS Specialists Meeting, Atlanta, GA., April 1986.

3. "Program KRASH Water Impact Upgrade," Draft Report, FAA/NAWC Contract DTFA03-89-00043.

4. Wittlin, G., Rapaport, M. B., "Naval Aircraft Crash Simulation Using Program KRASH, "American Helicopter Society Meeting, Washington D. C., May 1993.

5. Model Ditching Tests On The V-22 Osprey Aircraft, British Hovercraft Report No. EEL/ED/445, Issue A, Under Contract N0001985-C-0145 through Bell-Boeing, March 1987.