ROTARY WING AIRCRAFT WATER IMPACT TEST AND ANALYSES CORRELATION

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ABSTRACT

The Naval Air Warfare Center, Aircraft Division (NAWCAD) in cooperation with the Federal Aviation Administration (FAA) is sponsoring a Small Business Innovation Research (SBIR) Phase II program to investigate water impact dynamics relevant to DOD, DOT and industry. One of the primary objectives of the program is to develop analytical tools that can be used to facilitate the process of showing compliance with current civil and military ditching requirements with a decreasing dependence on expensive scale model ditching tests. This paper describes an effort that focuses on the application of a crash modeling and simulation approach utilizing both a nonlinear finite-element code (MSC/DYTRAN®) and a hybrid impact code (DRI/KRASH) to demonstrate the potential for airframe water impact analysis in the development of crash design criteria and concepts. The test recorded pressures, accelerations and damage from a fully instrumented UH-1H helicopter 26-ft/s vertical impact into water are presented. Pretest analyses using DRI/KRASH and MSC/DYTRAN® are provided and compared to the test measured results. Post-test modeling considerations and results are discussed and presented. Time histories of acceleration and pressure responses are included. A fuselage underside damage assessment is provided. A summary of overall averages and discrete point-by-point comparisons are included, as well as average pressures and floor pulses. The results presented are a partial fulfillment of the SBIR goals. Additional tasks on the SBIR are noted.

INTRODUCTION

Aircraft crashworthiness criteria, design approaches, and analysis methods have in the past focused mainly on ground impact conditions, without adequately accounting for fundamental differences associated with water crashes. This is because very little has been known about crash dynamics in water impact conditions beyond relatively low ditching levels, and the feasibility of designing future aircraft for combined ground and water impact crashworthiness. Since the U.S. Navy operates rotorcraft extensively over water, they have a strong interest in addressing this shortcoming by expanding crashworthiness knowledge in the area of water impacts. To accomplish this, the U.S. Navy initiated the water impact research described in this paper through a Small Business Innovation Research (SBIR) contract to Dynamic Response Inc., with subcontracts to Bell Helicopter Textron Inc, and Simula Technologies Inc. The objectives of this research, cosponsored by the Federal Aviation Administration (FAA), are to:

- Establish a crash modeling & simulation methodology that can be efficiently used by the rotorcraft industry and government to analyze aircraft and occupant responses to ditchings and more severe water crashes.
- Validate analytical methods by conducting full scale water crash tests and correlating results with simulation predictions.
- Apply analytical methods to investigate and propose improvements to crashworthiness criteria and design approaches that would provide combined ground and water crash protection.

The focus of this paper is to summarize initial results of the first water impact test, associated simulations, and to show the correlation between modeling and simulation.

Previously a paper was presented at the 1997 AHS Forum (Reference 1) which described the Phase I results of the current Phase II SBIR. In that paper it was shown that the use of current FEM and Hybrid programs like MSC/DYTRAN® and DRI/KRASH are capable of modeling water ditching and impact scenarios. During the Phase I effort accident data and scaled model ditching test data were utilized. However, there was a need to perform water impact tests to evaluate the capability of the aforementioned programs to analyze severe, but survivable water impacts. As part of the current SBIR effort it was determined to both model and test for two water impact conditions, using a fully instrumented UH-1H

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airframe. The SBIR effort benefited by having each test follow a Simula Technologies Inc. (STI) and U. S. Army Yuma Proving Grounds (YPG) test with limited instrumentation for a similar impact. The STI-YPG effort is described in Reference 2. The first test was a 26-ft/s vertical impact, 0° pitch airframe section impact onto water. This test, the pretest and posttest analysis comparisons are presented in this paper. The second test that has also been completed was a 28-ft/s vertical, 39-ft/s longitudinal, 4° nose-up pitch water impact with a full aircraft (skids and tail). The results of this test and associated analysis will be presented when the effort is completed.

UH-1H MODELS DEVELOPMENT

The approach presented in this paper utilizes computer codes that provide the greatest opportunity to achieve the stated 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 Figure 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.

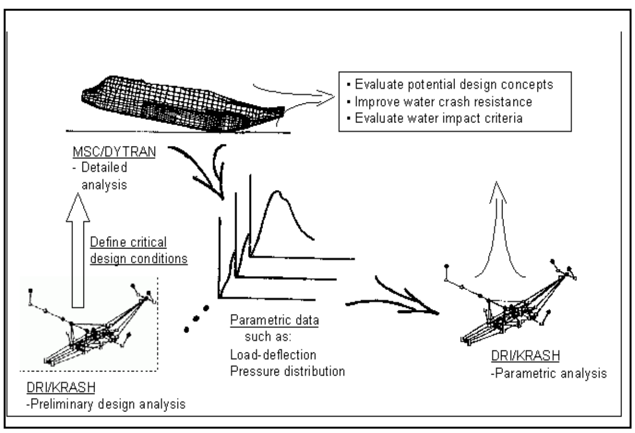
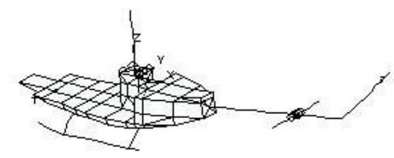


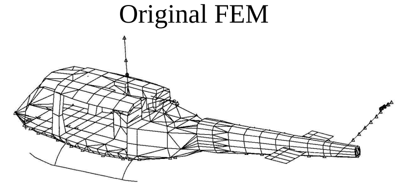
Figure 1. Combined FEM/hybrid approach.

Bell Helicopter Textron Inc. (BHTI) developed the MSC/DYTRAN† UH-1H Lagrangian model in the manner described below.

Development of the UH-1H MSC/DYTRAN® model began with a 1970's-vintage NASTRAN finite element model, (FEM), which was developed to analyze the first few natural modes. The original NASTRAN model was updated by adding much greater detail. The refined NASTRAN FEM was then converted to a MSC/DYTRAN® model. The added detail is evident by comparing the final FEM in Figure 2 with the original FEM. The philosophy used in modifying the FEM was to add the components and substructures or to add greater refinement to existing components and substructures that are expected to affect the crash analysis. Throughout the entire task, care was taken to maintain the same overall stiffness and fundamental dynamics (i.e., natural frequency placement) of the original finite element model.



Original FEM



Final FEM

Figure 2. Original and final MSC/DYTRAN® model.

Table 1 provides a comparison of the FEM before and after updating and shows the growth in the UH-1H FEM during this task. The FEM in Table 1 includes the tailboom and the landing gear. Key components of the structure were added to the basic FEM model. These included the roof, engine, detailed skin and floor structure, landing gear, and tailboom. Ballast was added as appropriate to emulate the planned test weight of 7290 lb.

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

Table 1. Structural Elements in the UH-1H NASTRAN MSC/DYTRAN® Model.

Component	Initial NASTRAN Model 1970's Vintage	Final NASTRAN/ MSC/DYTRAN® Model (with Tailboom)
Grid	216	2108
Cbar	173	1339
Shell	235 (incl. cshear)	2333
Conm (mass)	208	202
Other (celas, RBE, rod)	132	42
Total no. of elements	748	3916

The MSC/DYTRAN® Eulerian fluid and air gap models were added to complete the structure-fluid interaction. A 100-inch deep, 100 inch- wide, 340 inch- long –water model was developed using 8000 Eulerian CHEXA elements to represent the YPG fording basin. Two layers of air elements comprising 1600 CHEXA elements were added on top of the fluid to allow wave action above the initially quiescent water surface and to ensure that the Lagrangian-Eulerian coupling surface remained intact in the event of "bouncing" or "skipping" off the water surface. A MSC/DYTRAN® FLOW boundary was provided on the top surface of the air to prevent reflection of pressure waves from water that may contact this surface as well as to allow displacement of air that is displaced by the intrusion of the rotorcraft Lagrangian structure (i.e., "piston-syringe" phenomenon). In addition, MSC/DYTRAN® FLOW boundaries on all four sides of the water and air mesh were added to prevent reflected pressure waves from these surfaces.

The DRI/KRASH UH-1H model was developed in a manner similar to the development of the MSC/DYTRAN® model. The sequence of the model development is as follows:

1. A 1970's vintage KRASH UH-1H 31-mass, 37-beam model that was previously correlated with a full-scale ground impact test was utilized as the basis of the study.
2. Utilizing BHTI provided mass data, a 3-D drawing and the NASTRAN model the DRI/KRASH model including the engine, transmission, seat/occupant locations, was developed. This model was initially set up with external crush springs and a skid and tail.
3. The crush springs were removed since this was to be a water impact model. The tail and skids were also removed since they were not present in the 1st SBIR test (designated as S1).
4. The number and location of water contact surfaces were set up to be consistent with the intended pressure locations on the test vehicle. For each panel the surface area, and representative shape were determined and input to the model. Based on prior analysis of the STI-YPG first test (designated as C1), a spherical shape with a radius of 100-200 inches was selected. Approximate failure forces and pressures were determined from the respective panel properties, i.e. thickness, material and using thin membrane stress theory. The hydrodynamic aspects of the DRI/KRASH program, along with its other features, are discussed in Reference 3.
5. The model was changed and expanded to represent masses placed on the floor in lieu of occupants/seats, masses added to be consistent with the test vehicle, and restraint beams that were used to tie down masses on the floor. Ballast was added as appropriate to emulate the planned test weight and cg.

The original and final models are shown in Figure 3. The final full model for the S1 test (without tailboom and skids) consists of 138 masses, 290 beams, 37 node points, and 27 hydrodynamic surfaces.

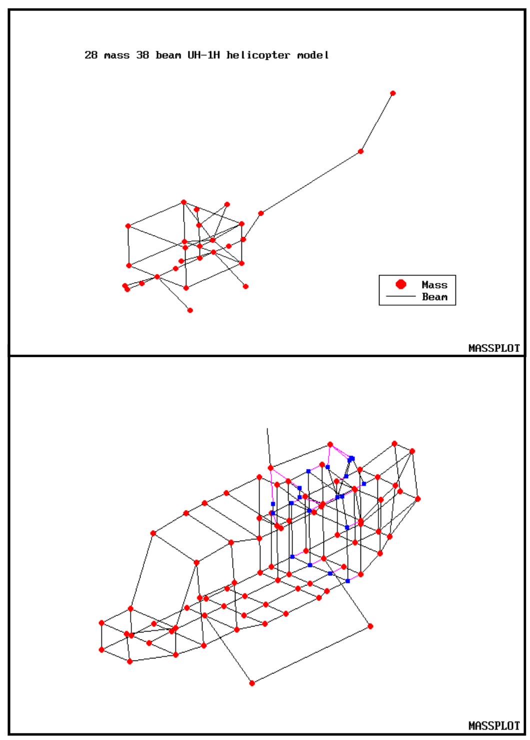


Figure 3. Original and final DRI/KRASH Models

SBIR TEST NO. 1 (S1)

Figure 4 shows several survivable impact envelopes developed by the FAA, U.S. Army and U.S. Navy for ground and water impacts. Noted in Figure 4 are the impact conditions for the SBIR tests (S1 and S2) and the STI-YPG combined impact test (C2). The first STI-YPG test (C1) was performed at 24 ft/s vertical, but with a total weight of approximately 1450 lb., compared to a ready-to-fly weight of 5260 lb. All the other test articles were at weights between 7570 and 8000 lb.

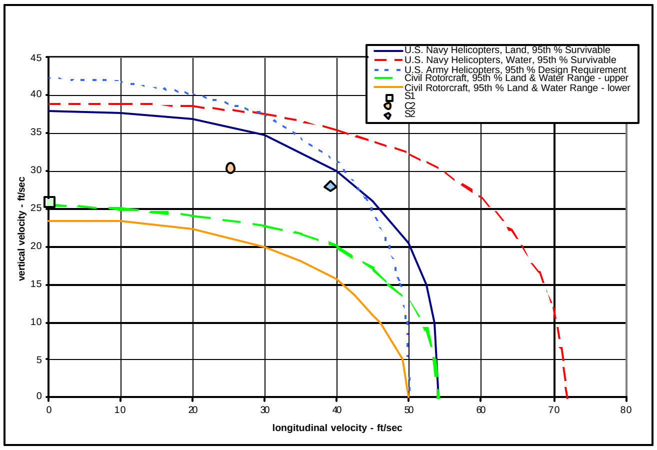


Figure 4. Impact envelope and test conditions

The S1 test was performed at YPG on December 16, 1998. The impact condition was 26 ft/s vertical sink speed with no or minimal forward velocity, pitch, roll or yaw. A total of 30 accelerometer and 30 pressure responses were recorded. Prior to the test being conducted photographs were taken of the test instrumentation, the major mass simulated items and the underside of the aircraft. The test impact is shown in Figure 5. The test data was processed using a 4^{th} order filter with a cutoff frequency of 300 Hz., using a SAE class 180 filter per SAE J211/1. The data from the slab mass measured acceleration at fuselage station (FS) 84.5, buttline (BL) 14 was integrated (Figure 6). The results showed that the free fall after release begins at around 1.2 sec, with a -1g acceleration until water impact at around 2.0 sec. Peak vertical velocity is about –26 ft/s (down), and the integrated distance is essentially zero at water impact. The vehicle rapidly decelerates to around –6 ft/s within around 2.10 sec., then more gradually decelerates to zero vertical velocity at around 2.8 sec. At about 2.1 seconds the water penetration is estimated to be about 1 ft. Beyond that point, the vehicle rebounds very slightly, then resumes sinking.

Figure 5. S1 test impact

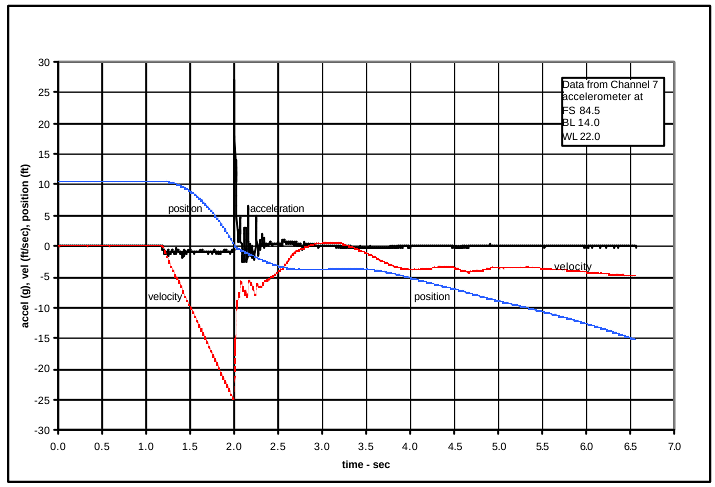


Figure 6. S1 test vertical acceleration, integrated velocity and position

The average floor peak acceleration measured for all the locations in the vertical direction is around 57 g. This is reduced to 45 g when all pulses greater than 100 g is eliminated. The floor peaks range from 27.2 g measured on the occupant simulated slabs at FS 84.5 and 24.5 on average at FS 155 to as high as 175g at FS 136, BL 36.3 measured directly on the floor. The slab measurements at FS 84.5 and FS 155.06 provide some indication of the cg vertical acceleration magnitude of the airframe. FS 155.06 is closer to the airframe cg, and it reads on average 24.5 g. Of interest is that the right and left side acceleration measurements differ sharply at some locations. The acceleration variation between the left and right side averages 22.5 % over 7 locations, with a high of 63.2 % at FS 129, BL ±36.3.

The average peak pressure measured is approximately 30 psi. The left and right side measurements of pressure vary somewhat, as is the situation for the acceleration responses. For 10 such fuselage stations where opposite side measurements were made the variation is 20.3 % on average. The variation is from less than 5 % at 3 locations to as much as 45 % to 49 % at two other locations. The measurement at channel no. 8 (FS 80.75 BL –5.25 was lost). Several other measurements are suspect. Centerline pressures from FS 83 and aft appeared to be extremely low and inconsistent with the severe damage that was observed in this region.

The fuselage underside damages after the test is shown in Figure 7. A substantial number of underside panels exhibit deformation and varying degree of failure. As many as 23 of the 30 monitored panels may have been moderately to severely damaged. The center of the airframe is permanently bowed, which indicates that the centerline panels have been severely damaged, which the post-test photographs confirm. It was observed that the fuselage underside centerline panels suffered severe damage, particularly from FS 73 and aft. Forward of FS 83 the panels appear to show some deformation, but not severe damage. Also the panels outboard of BL 14 suffered significant damage from BL 102 and aft, most notably under the transmission and where the fuel cells are normally located.

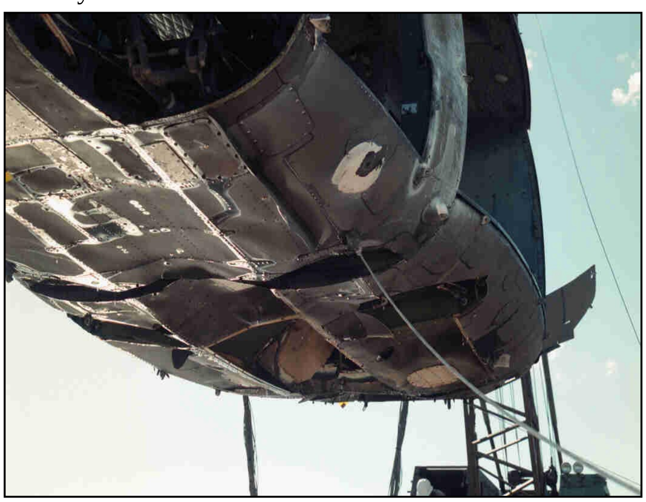


Figure 7. S1 test underside damage

ANALYSIS VS. TEST

Both MSC/DYTRAN® and DRI/KRASH pretest analyses were performed. In addition several posttest analyses were performed. The pretest analysis was based on an anticipated vehicle weight of 7290 lb. The actual test weight was 7570 lb. Posttest analyses took the weight difference into account. The following modifications were made for the DRI/KRASH model:

- Concentrated masses were added to the model to be consistent with the slab masses that were added to the test article airframe to represent occupant and tail section weights. Appropriate tie-down beams were added.
- Hydrodynamic lift surfaces were redefined to agree more closely with the location of pressure transducers. These included four additional lift surfaces that were added at the landing gear skid wells at FS 63 – 74.3 and FS 155 –166 locations and the addition of surfaces at FS 155 – 166.
- Global changes affecting all the responses, and not selected local responses were investigated. These included the use of a hydrodynamic factor (HF), an effective radius change, and the introduction of panel design failures.
- The acceleration and pressure responses were filtered using the SAE Class 180 digital filter in accordance with SAE J211/1 to be consistent with the filtered test data.

For the MSC/DYTRAN® posttest analyses included:

- Changing the weight to 7570 lb.
- A bilinear yield model using the Von Mises yield criterion (YLDVM) with isotropic hardening, along with a maximum plastic strain failure model (FAILMPS) was applied to all the aluminum panels. Failure will occur if the maximum plastic strain exceeds the specified value.
- The acceleration and pressure responses were filtered using the SAE Class 180 digital filter in accordance with SAE J211/1 to be consistent with the filtered test data.
- The modeling of Sandwich belly skin panels was redefined. In the pretest model, the sandwich panels were modeled as single-layer shell elements with a thickness equal to the sum of the face sheets' thickness to account for the membrane stiffness. The out-of-plane bending stiffness of each sandwich panel was provided through the use of bar elements that were added in parallel around each shell element. However, while preserving overall panel stiffness this model does not preserve the panel strength. In the posttest model, the bar elements were eliminated, and the sandwich panels were replaced with multi-ply laminate composite shell elements (PCOMP). Orthotropic material properties (MAT8) for each sandwich layer were defined, along with orthotropic failure material properties (MAT8A). A maximum stress failure theory was applied to face sheet materials and a maximum shear failure theory was applied to core materials.

Several time-history comparisons between the analysis and the test results for both the pretest and posttest modeling are shown in Figures 8-15. Figures 8 and 9 show DRI/KRASH pretest and posttest acceleration comparisons with test data at FS 42 BL 14 and FS 155 BL14, respectively. Figures 10 and 11 show DRI/KRASH pretest and posttest pressure comparisons with test data at FS29 BL 14 and FS 81 BL20-

24, respectively. Figures 12 shows MSC/DYTRAN® pretest and posttest acceleration comparisons with test data at FS 155 BL –20. Figures 13 shows MSC/DYTRAN® pretest and posttest pressure comparisons with test data at FS45 BL23. Figures 14 and 15 show D modeling improves the comparison, while in others the opposite occurs. The latter two figures (Figures 14 and 15) are of interest because the centerline damage is obvious in the posttest observations and photographs. Yet, the measured responses do not reflect significant forces, as the analysis does. An explanation may lie in the possibility that the pressure transducers may not have correctly responded.

The comparisons in these figures provides some indication of both the test measured responses and the analytically determined pulses with regard to pulse shape, magnitude, time of occurrence and rise time. In order to assess the validity of the analyses it is necessary to establish criteria. For this study two levels of agreement were used to assess the agreement between test and analysis. The first is agreement within 20 % of peak pressure and acceleration and within 5 milliseconds of peak occurrence. The second and less stringent tolerance is within 25% of peak pressure and acceleration, and within 10 milliseconds of peak occurrence. In addition to the acceleration and pressure comparisons underside panel damage assessment was taken into account. A comparison of the analysis and test point-by-point results for the pretest and posttest MSC/DYTRAN® and DRI/KRASH results are depicted in Figure 16. The analysis compared up to 150 data points and showed the following agreement with test data:

<u>DRI/KRASH pretest (posttest) results</u>

- Point-by-point peak acceleration of 64 % (55 %)
- Point-by-point pressure of 57 % (62 %)
- Point-by-point panel damage of 82 % (60 %)

<u>MSC/DYTRAN® pretest (posttest) results</u>

- Point-by-point acceleration of 48 % (52 %)
- Point-by-point pressure of 47 % (41 %)
- Point-by-point panel damage of 66 % (73 %)

A comparison of the analysis and test overall results for the pretest and posttest MSC/DYTRAN® and DRI/KRASH results are depicted in Figure 17. The analysis showed the following percentage difference with the test data:

<u>DRI/KRASH pretest (posttest) results</u>

- Average acceleration –7.5 % (+8.9 %)
- Average pressure –29.6 % (–16.8 %)

<u>MSC/DYTRAN® pretest (posttest) results</u>

- Average acceleration +15 % (+19.3 %)
- Average pressure +38.3 % (+33.9 %)

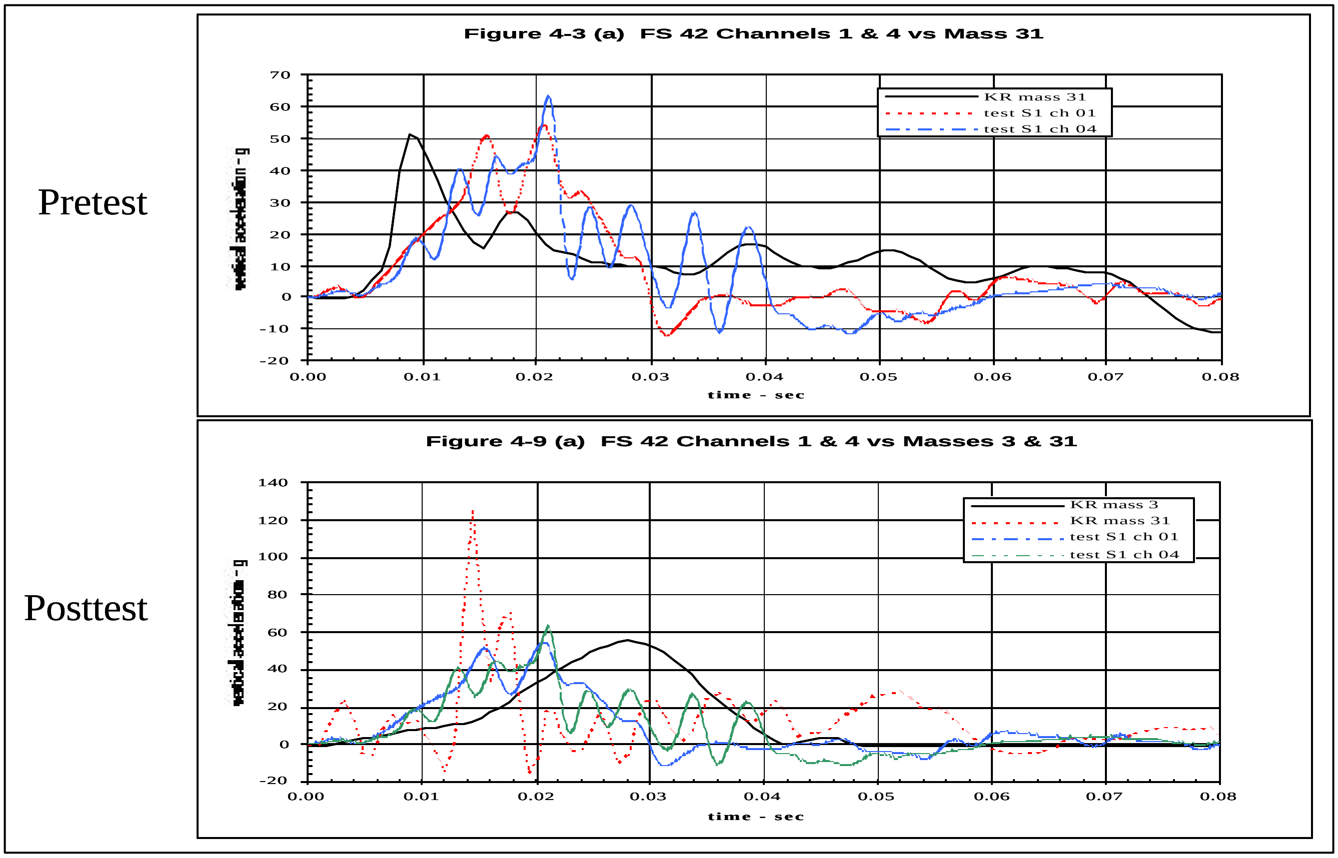


Figure 8. S1 pre & posttest accelerations – FS 42 BL 14 – DRI/KRASH vs test

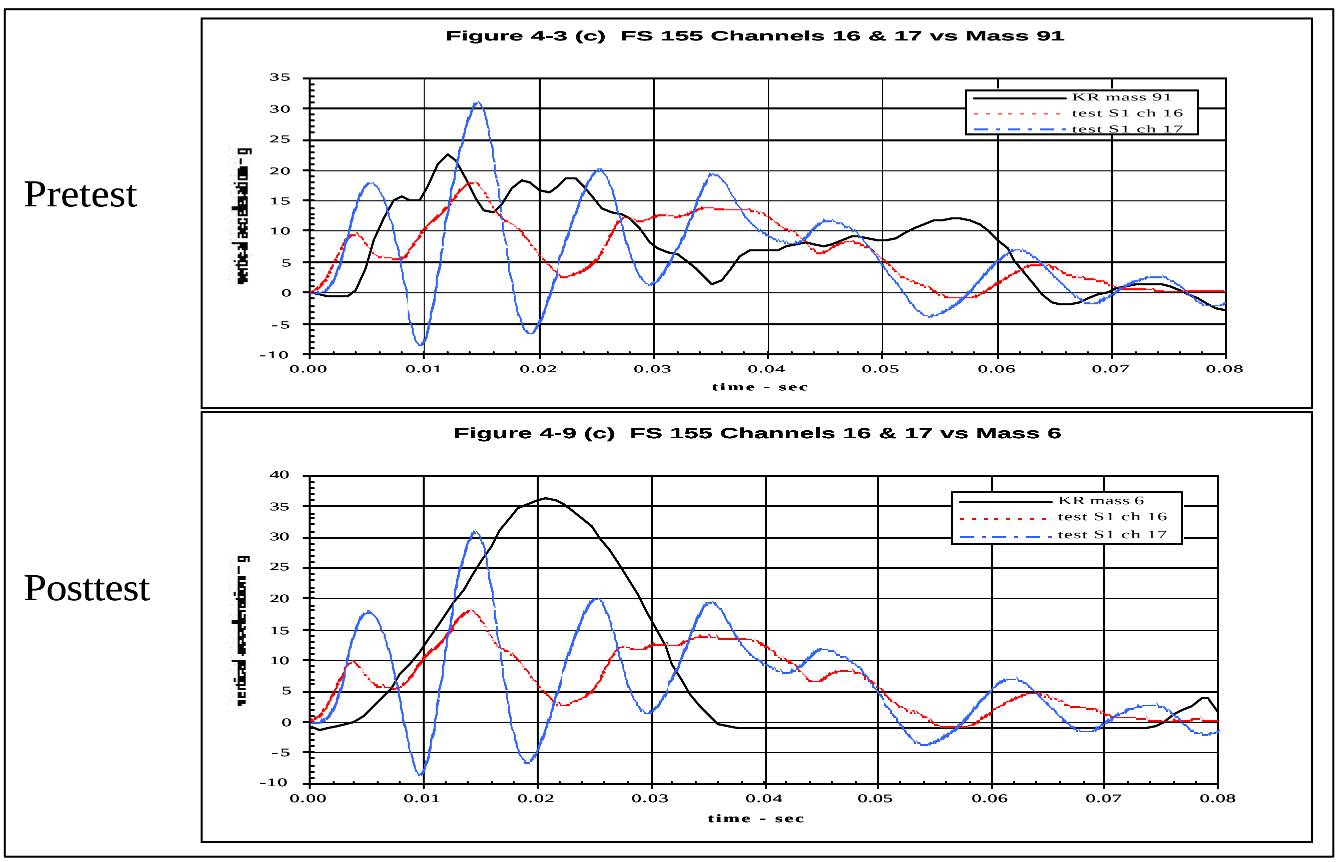


Figure 9. S1 pre & posttest accelerations – FS 155 BL 14 – DRI/KRASH vs test

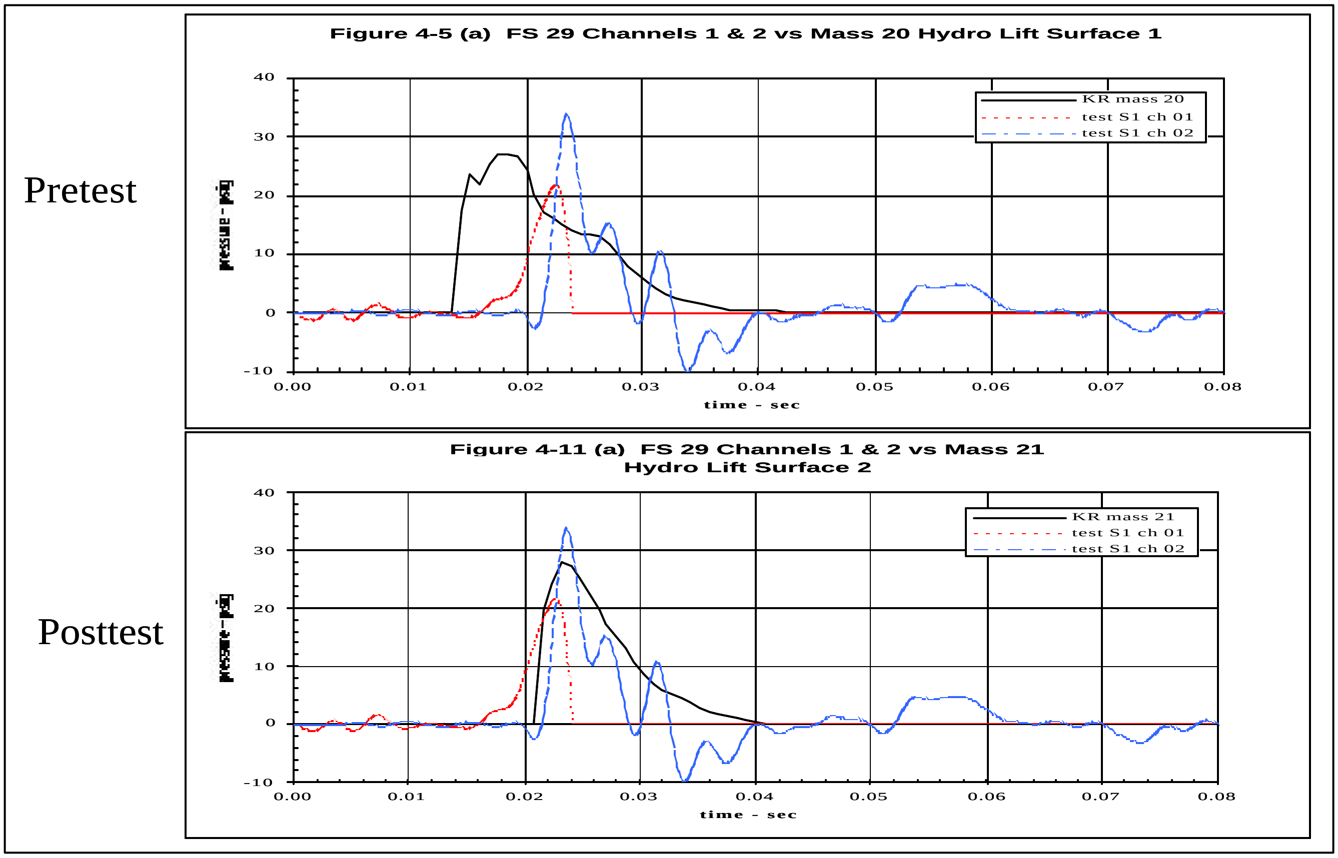


Figure 10. S1 pre & posttest pressures – FS 29 BL 20-24 – DRI/KRASH vs test

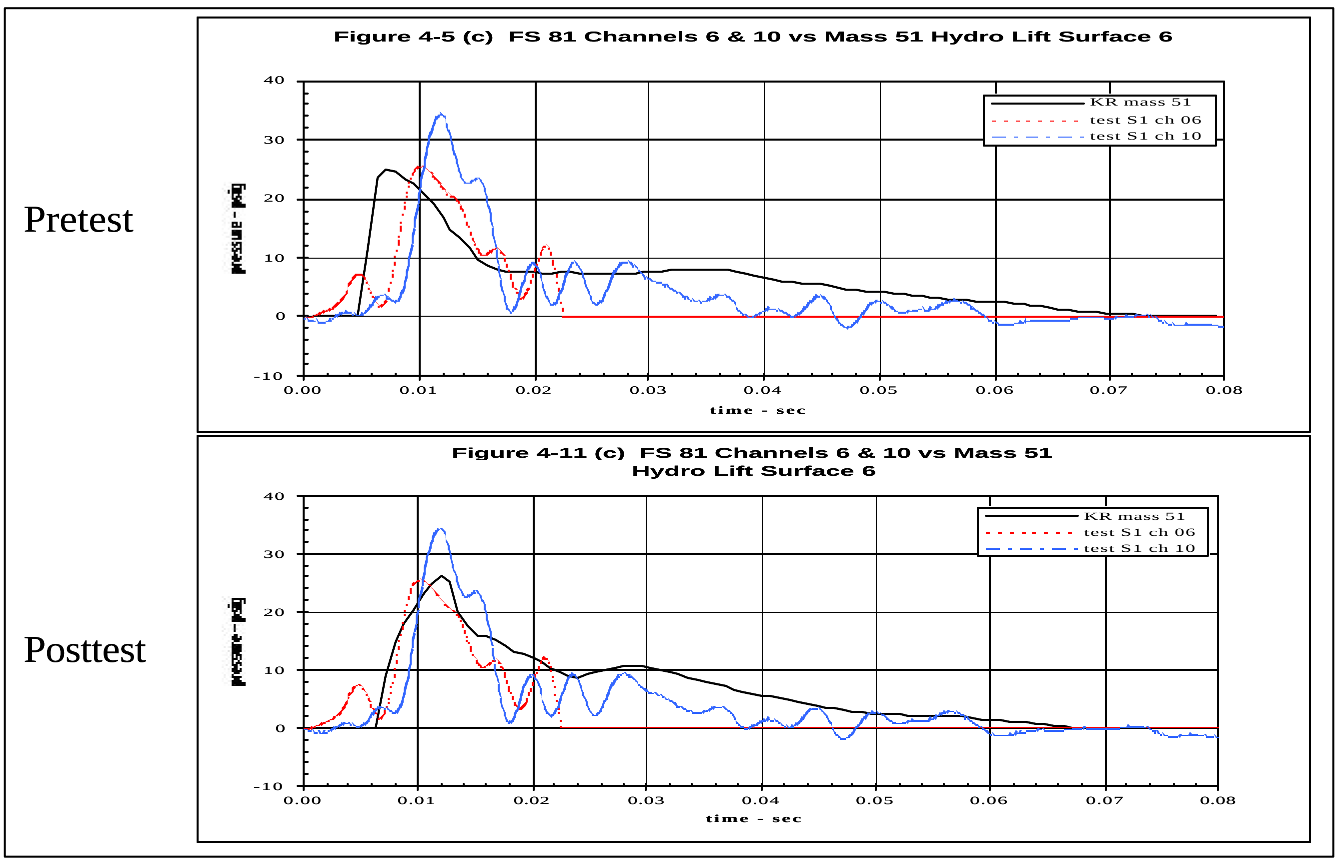


Figure 11. S1 pre & posttest pressures – FS 81 BL 20-24 – DRI/KRASH vs test

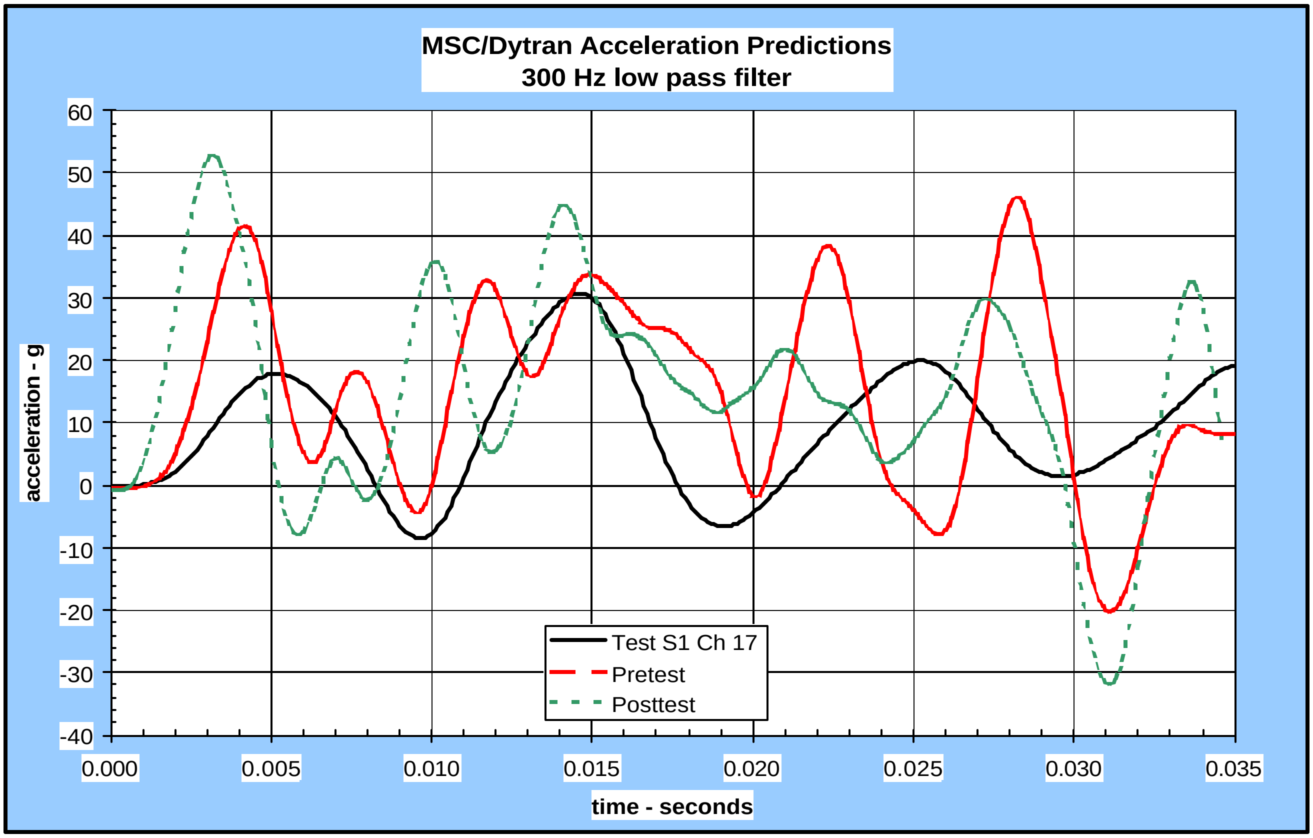


Figure 12. S1 pre & posttest accelerations – FS 155 BL 20 - MSC/DYTRAN vs test

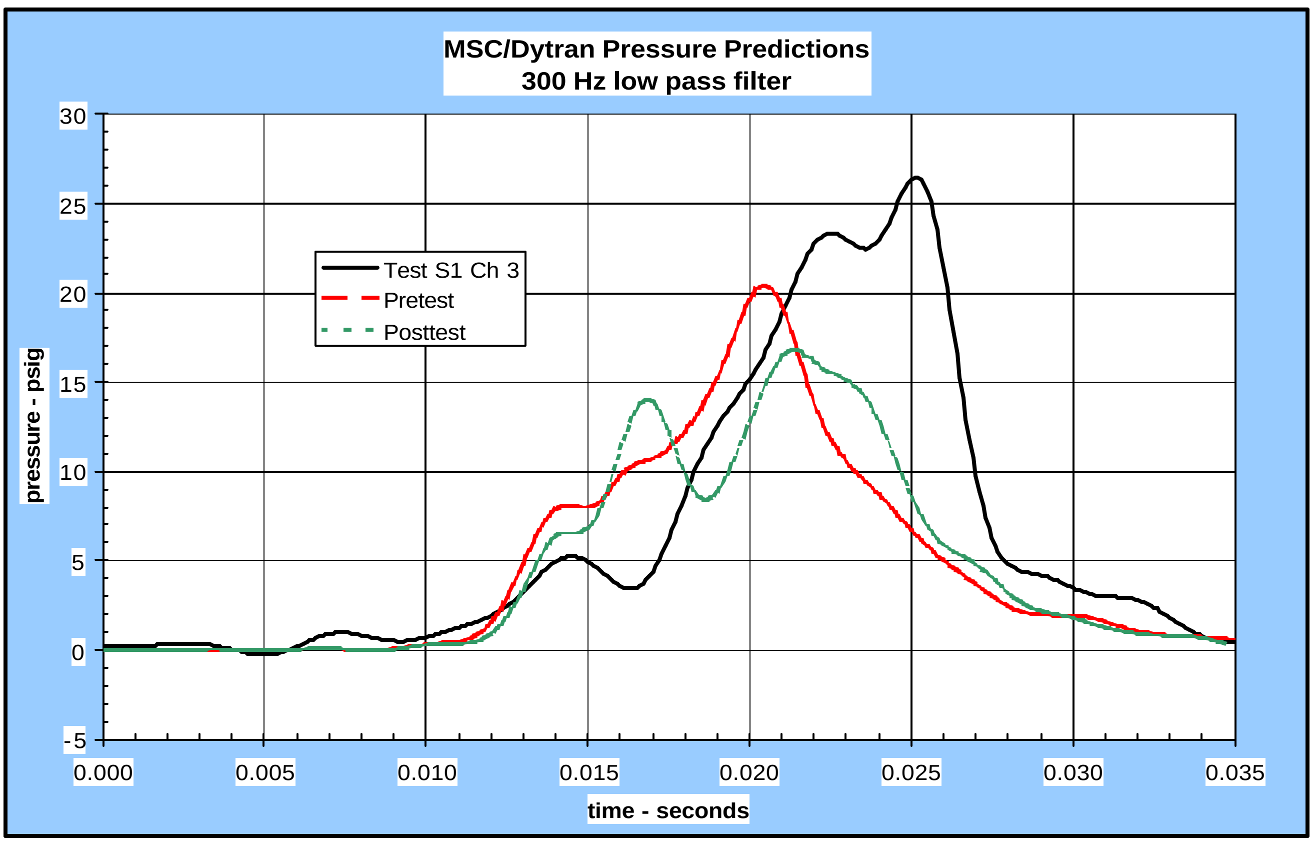


Figure 13. S1 pre & posttest pressures – FS 45.25 BL 23.25 - MSC/DYTRAN vs test

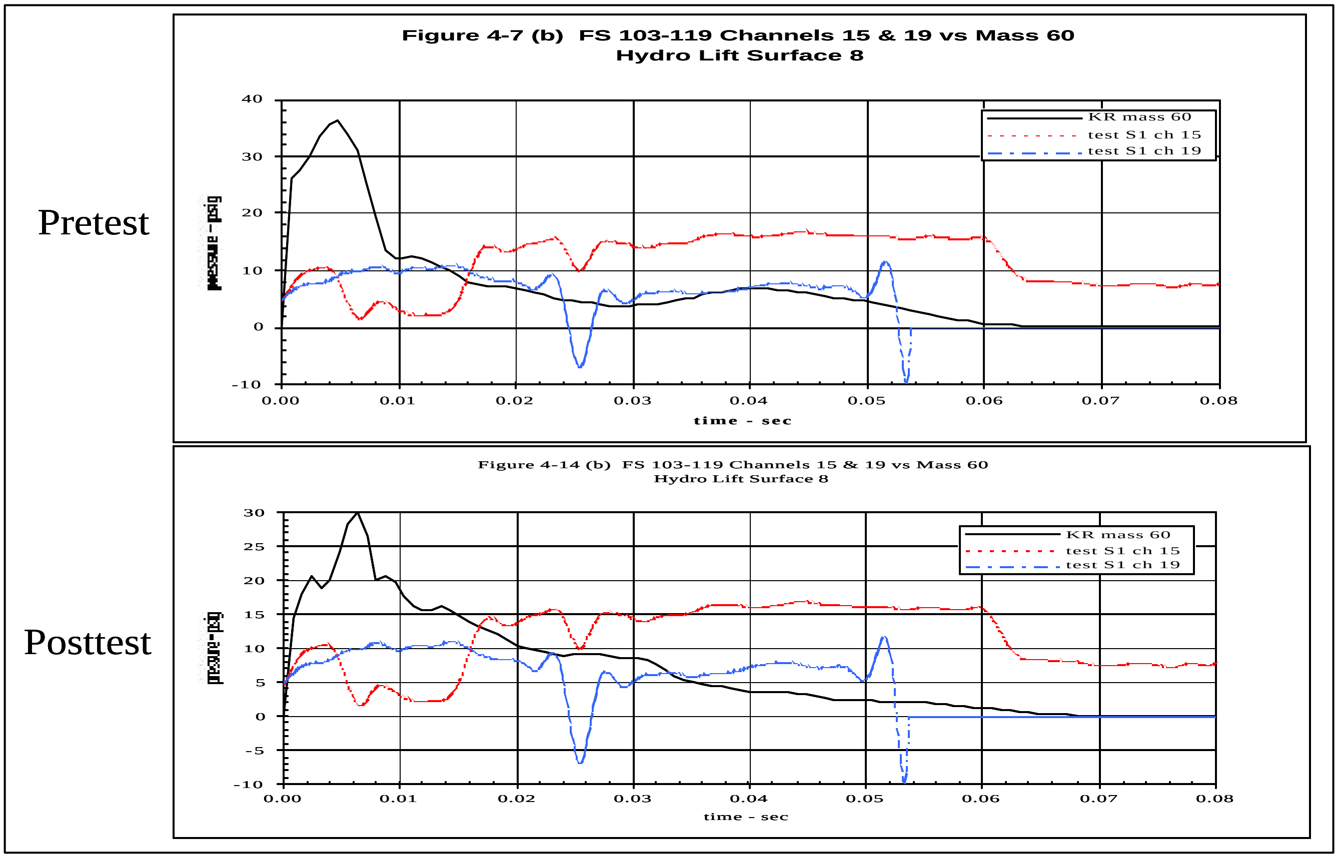


Figure 14. S1 pre & posttest pressures – FS 103-119 BL 0 – DRI/KRASH vs test

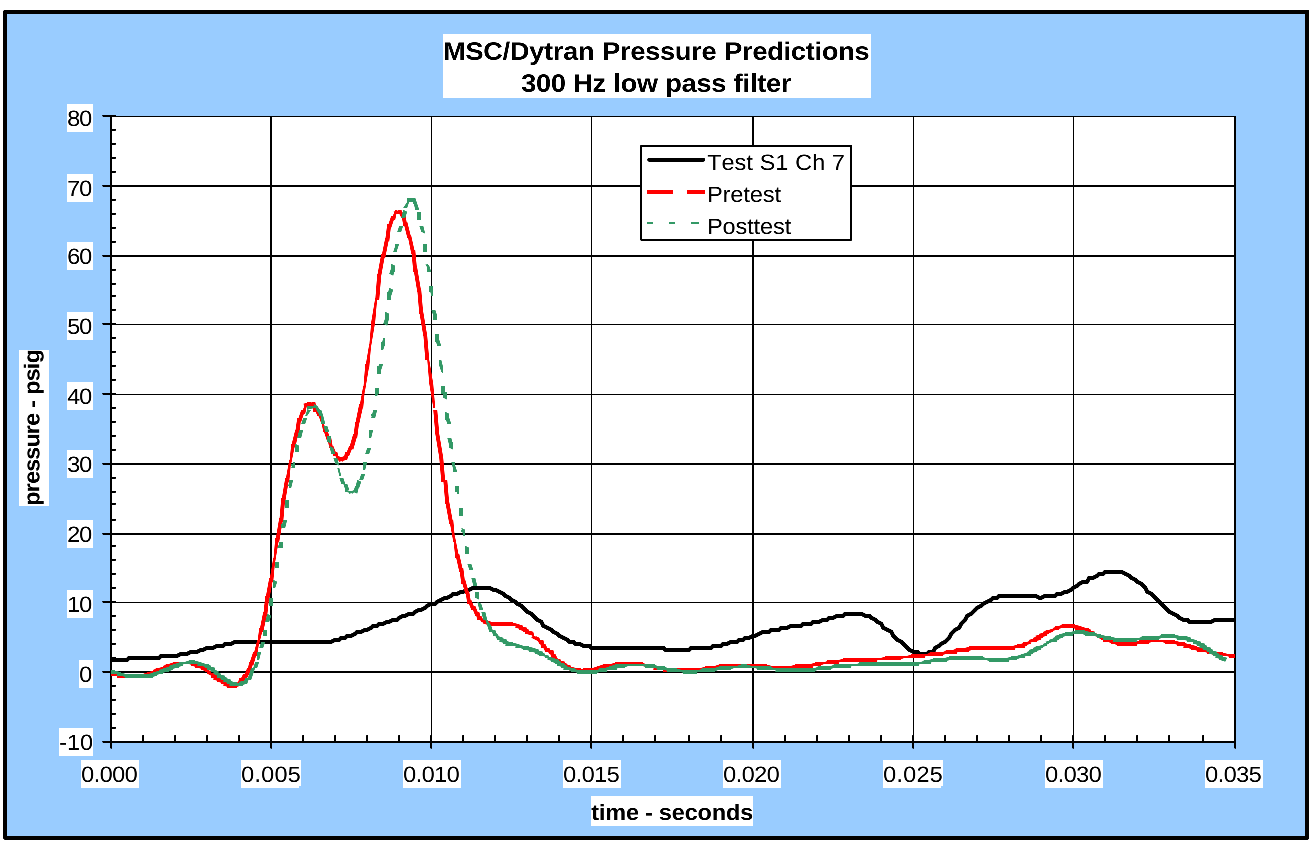


Figure 15. S1 pre & posttest pressures – FS 83.759 BL –1.18 – MSC/DYTRAN vs test

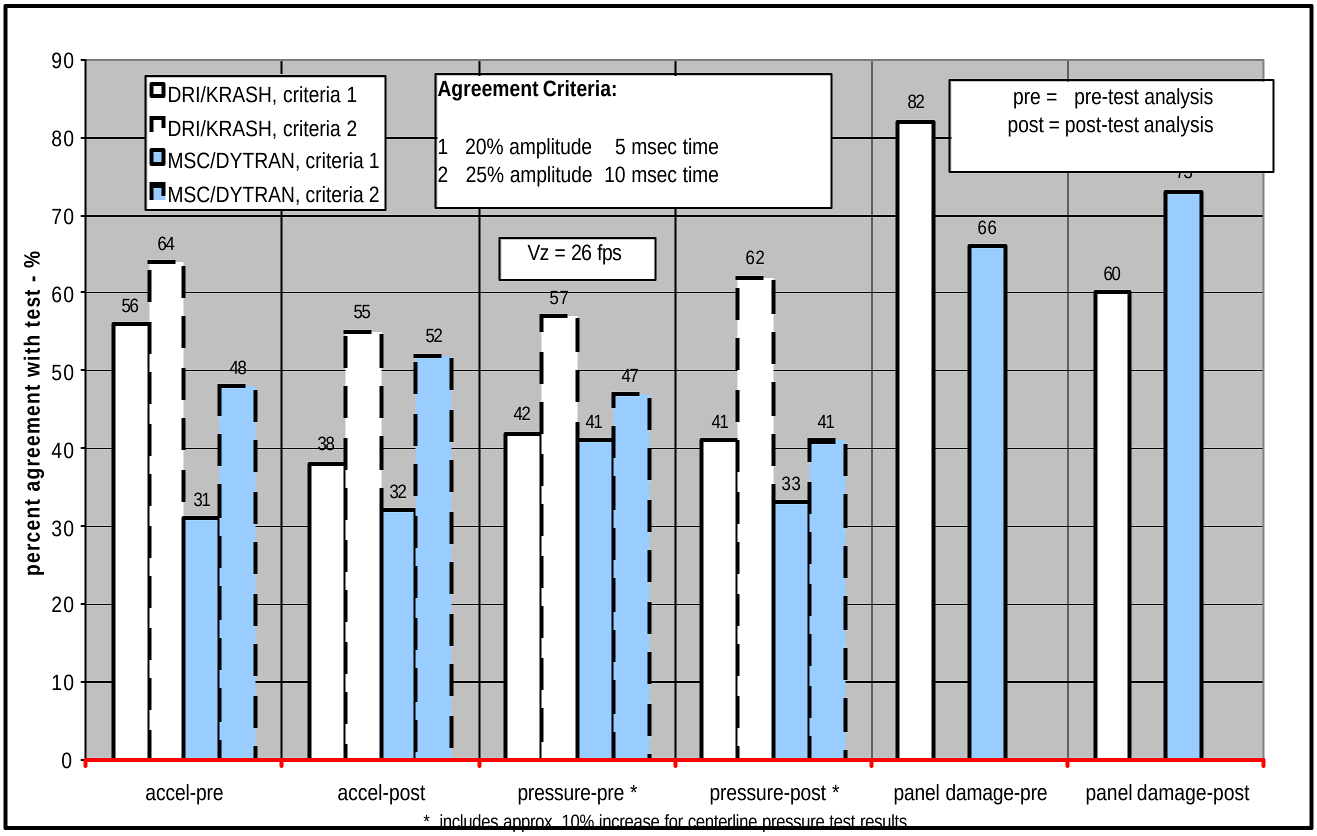


Figure 16. Analysis vs test data - discrete

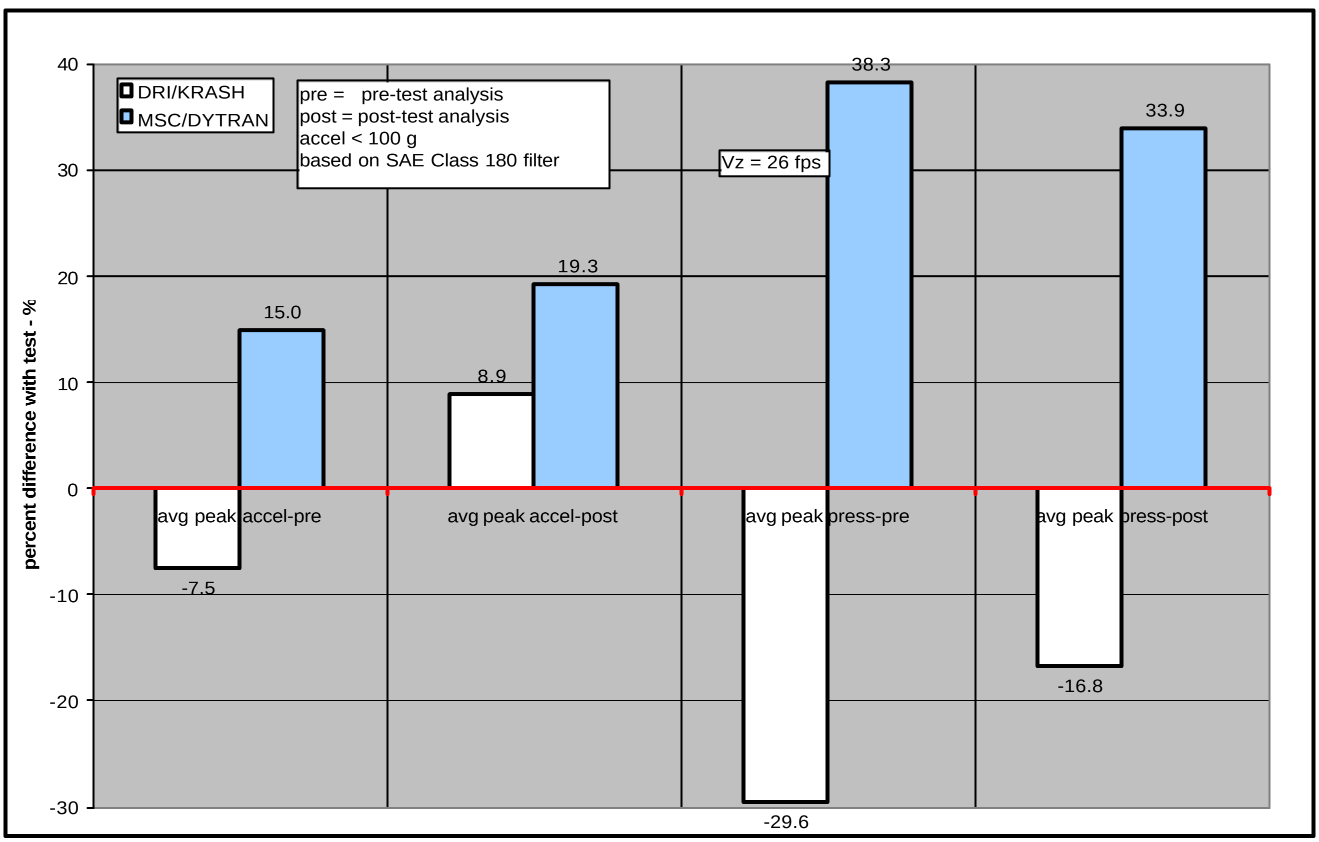


Figure 17. Analysis vs test data - overall

DISCUSION OF RESULTS

Of the 60 acceleration and pressure data channels recorded, only 1 channel was considered lost at the initiation of water impact. Several channels recorded data for sufficient time before losing data. Several responses were considered questionable in the sense that the magnitudes were not consistent with the damage that was experienced.

Overall the 26-ft/s water impact vertical velocity caused substantial, but not devastating damage. A number of underside panels, perhaps 75 % of the total monitored suffered some form of damage. The interior floor panels did not appear to suffer secondary water impact. The extent to which occupants might have suffered injuries can not be assessed without examining the dynamic responses associated with the seat/occupant at particular locations.

The pretest DRI/KRASH analysis appears to have been sufficiently adequate to describe the potential level of impact necessary to sustain severe, but survivable loads, as depicted by damage prediction and level of responses. The posttest analysis investigation to improve the model with regard to its representation of the actual test configuration, as well as to parametrically evaluate some modeling factors showed that improvements could be achieved. However, although some parameters were shown to match the test data better, there were other parameters that actually compared less favorably. It was possible to get agreement between analysis and test data for overall comparisons to less than 20 %. Several additional posttest analyses were performed with DRI/KRASH to evaluate the effect of selected global changes to the input. These included changing input parameters such as Hydrodynamic Factor (HF), effective radii, and effective area. The average of 4 cases was used to obtain the posttest DRI/KRASH results.

The MSC/DYTRAN® posttest analysis, as in the case for the DRI/KRASH analysis, resulted in some improvements, but also some less favorable results. The pretest MSC/DYTRAN® results show agreement within 34 % for average pressure and 15 % for average acceleration.

The point-by-point (discrete) comparison of analysis versus test results is based on up to 150 data points. That consists of 30 channels each of pressure peak, time of pressure peaks, acceleration peaks, respective times of occurrence, and 30 panel locations. Thus when the agreement reaches 65 % it means that nearly 100 points have satisfied the criterion that was selected.

Both the test and analyses data were based on an SAE Class 180 (300 Hz.) filtered signal. The approximate floor pulse characteristics (based upon responses less than 100 g) for the configuration exposed to a 26-ft/s vertical impact are shown below with regard to peak acceleration, rise time, and onset rate:

- Test data: 45.3 g, 0.0135 sec, 3365 g/sec
- MSC/DYTRAN analysis: 51.0 g, 0.0100 sec, 5100 g/sec
- DRI/KRASH analysis: 53.3 g, 0.0153 sec, 3473 g/sec

The corresponding average fuselage underside pressures are listed below. Analytical results are shown as ranges based on pre and post test results.

- Test data: 30 psi
- MSC/DYTRAN analysis: 34-39 psi
- DRI/KRASH analysis: 22-27 psi

It is difficult to compare some aspects of the MSC/DYTRAN® and DRI/KRASH analyses because of the differences that exist in modeling philosophy. For example, some output readily available in one program may not be available in the other. The FEM analysis provides stress, deformation, and plasticity contours, which are not available from the hybrid model. The hybrid model easily allows for global model input parameter changes such as HF, area and shape, as noted earlier. The FEM model is designed to model very discretely. Introducing broad overall changes to the FEM model is very difficult, unlike the hybrid model.

The hybrid models exhibit the distinct advantage of being able to perform parametric type studies in that their model development costs and run time are substantially less than those of the FEM. In this effort the model development time for the FEM model is three-fold that of the hybrid model. Also, in this effort the hybrid model executed the water impact simulation in one to two minutes on a PC, versus 10 to 12 hours for the FEM model on a workstation. Noteworthy is that the analyses agree with each other, but not with the test data in some areas. For example:

- The engine and transmission peak accelerations from the DRI/KRASH analysis are 28.5 g and 34.0 g, respectively. The corresponding MSC/DYTRAN® results are 26.6 g and 43.2 g, respectively. That is only 9.2 % and 21.3 % differences. The test results for these two masses are 16.7 g and 13.1g, respectively.

- The test results indicate substantial failure at the centerline from FS 103 and aft, despite the low measurements. Both computer codes show substantial pressures (greater than 34 psi) do occur at these centerline locations, and that failure criteria will likely be exceeded (Figure 14 and 15).

Both analyses provide a reasonable assessment of the panel damage associated with the water impact forces, when one considers that 65-80% agreement is achieved in both the pretest and posttest analyses.

The DRI/KRASH model provides design pressures as criteria and considers water forces/pressures that approach within 90% of these values or exceed such values as potentially damaged structure. Those panels that exceed design pressures are allowed to fail and adjacent structure can be impinged on. The MSC/DYTRAN® analysis incorporates plastic strain theory for metallic skins and several failure modes for sandwich construction. The combination of yield, plastic deformation and sandwich panel failure modes is used to determine potential damage.

CONCLUDING REMARKS

The information presented in this paper is a partial fulfillment of the SBIR tasks and goals. Several tasks remain to be completed including;

1. The evaluation of the combined velocity water impact test and analyses results.
2. Analysis of existing scaled model ditching test results of a 46,000 lb. VTOL aircraft. To this end approximately 35 available scale model ditching test impact conditions have been analyzed using DRI/KRASH. Included are the following range of conditions:
   - Sink speed; 4.5, 6.0, 10.0, 15.0 ft/s
   - Aircraft weight; 34K, 42.6K, 60.5K lb.
   - Pitch attitude; 0°, 5°, 10°, 15° nose-up
   - Roll; 0°, 5°, 16.5°, 23°
   - Forward Velocity: 20-30-40-45-50-56 knot
   - Lift; 67%, 100%
   - Sea State; Length/height ratios of: 75/7.5, 75/3.75, 52/2.58
   - Special Operating Conditions, i.e. one engine inoperative (OEI): 120 knot forward velocity, 12 ft/s sink speed
   - Evaluation of current military and civil aircraft ditching requirements and compliance procedures utilizing the ditching and impact tests and analyses results.
   - The integration of the SBIR data and methodology with other aspects of water impact, i.e. flotation systems, ground/soil impact and civil category aircraft.
   - The development of inputs for potential water impact design criteria using SBIR tests and analyses data, as well as existing seat dynamic pulses from current requirements of military and civil rotorcraft.

The results presented in this paper compare two distinctly different types of programs (hybrid and FEM) used to perform analyses of a specific test condition. The pretest analysis results are considered representative of the demonstrated level of the responses and damage experienced during the test. The results and subsequent discussions support the contention that both types of programs can be effectively utilized as complementary, not competitive tools.

Validation of model capability is dependent on the criteria that are established in the assessment process. Matching analysis and test on a discrete point-by-point basis is difficult, if not impossible, if the goal is to have all 30 accelerations and all 30 pressure responses and damage to 30 panels be in agreement. When one considers peak value, time of occurrence of peaks, and panel damage, there are nearly 150 test points to compare to. The analyses for the S1 test showed a discrete comparison agreement of 64 % for acceleration, 62 % for pressure and 82 % for panel damage with test results. Bear in mind that an overall agreement of 64% means that approximately 100 data points are matching. Perhaps a more rational assessment of the validity of the analytical modeling capability is the ability of the model to realistically depict the damage and response levels that were experienced during the test.

The presumption that analysis must match all the test data to be valid may not be the only basis to accurately determine analysis capability. The previous discussions have shown that the test data has scatter, variations, and in some instances inconsistent magnitude levels. The analyses provide results that generally match the test data as can be noted in the discrete and overall comparisons, and the associated average pulse characteristics, such as peak g, rise time and duration.

It must also be noted that the results are for one test condition, one test article, one step in the process, and thus at this point in time can only be considered a start of and not a final assessment of water impact design criteria.

These results show that the combination of FEM and Hybrid crash simulation is a promising analytical approach that can be used to develop next generation crashworthiness systems so that significant water impact protection is included. This enabling technology will facilitate development of future joint service rotorcraft, civil rotorcraft, and their subsystems by permitting designers to incorporate combined ground and water impact crashworthiness features.

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