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Simulation of X-38 Landing Scenarios With Landing Gear Failures

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Abstract

Abnormal landing scenarios of the X-38 prototype Crew Rescue Vehicle (CRV) were modeled for three different cases involving non-deployment of landing gear with an explicit dynamic nonlinear finite element code, MSC/DYTRAN. The goal of this research was to develop models to predict the probability of crew injuries. The initial velocity conditions for the X-38 with chute deployed were 10 ft/s vertical and 57 ft/s longitudinal velocity. An MSC/NASTRAN structural model was supplied by JSC and was converted to a dynamic MSC/DYTRAN model. The MSC/NASTRAN model did not include seats or floor structure; thus, the acceleration of a lumped-mass attached to the bulkhead near each assumed occupant location was used to determine injury risk for each occupant. The worst case for injury was nondeployment of all gears. The mildest case was nondeployment of one main gear. Although a probability for minor injury was predicted for all cases, it is expected that the addition of energy-absorbing floor structure and seats would greatly diminish the probability of injury.

Introduction

Abnormal landing scenarios of the X-38 prototype for the Space Shuttle Crew Rescue Vehicle (CRV) were simulated by the crash dynamics group, located at the Impact Dynamics Research Facility (IRDF) of the NASA Langley Research Center (LaRC). The goal of this research, which was requested by NASA Johnson Space Center (JSC), was to develop models to predict the probability of crew injuries in the case of landing gear failures. The nonlinear dynamic finite element code, MSC/DYTRAN (ref. 1), and the dynamic mechanical modeling code, DADS (ref. 2), were used at LaRC in this modeling effort. The project was begun late in June 1999, and due to a tight schedule, it was requested that the LaRC team complete the simulations by September 1, 1999. A preliminary draft of this report was transmitted to JSC before the deadline.

Three landing scenarios were simulated for the X-38 as requested by JSC. All simulations assume that the X-38 lands on a dry lakebed with a friction coefficient of 0.8. Since the X-38 uses skid landing gear, the friction coefficient is important in the simulations. The initial velocity conditions for each simulation were 10 ft/s vertical and 57 ft/s longitudinal velocity. The three cases investigated were:

<u>Case 1</u> – all three landing gear do not deploy (gear-up)
<u>Case 2</u> – the nose gear does not deploy (nose gear-up)
<u>Case 3</u> – one main gear does not deploy (starboard gear-up).

JSC supplied LaRC with a static MSC/NASTRAN model and a dynamic DADS model of the X-38. The MSC/NASTRAN model contained approximately 20,000 elements and was designed for linear static and normal mode analysis. The DADS model consisted of landing gear attached to a rigid body to simulate various landing scenarios. An MS-DOS personal computer (PC) program *Dynrespn* was also supplied by JSC to calculate injury based on the Dynamic Response Index (DRI) injury criteria (ref. 3 - 5).

The MSC/NASTRAN model from JSC did not include seats or floor structure; thus bulkhead accelerations at the assumed occupant locations were used to determine injury risk factors for the occupants. Each 204-pound occupant was simulated by two lumped masses weighing 102 pounds. The masses were attached to the top of bulkhead frames at body stations (BS) 91 and 191 where the floor would likely be attached, see Figure 1 which follows the text. There were a total of six occupants (and thus 12 masses). The two front passengers were at BS 91; and the four back passengers were located at BS 191.

The following sections of the paper will describe the model development process and the simulation results for three landing scenarios. The paper concludes with a comparison of injury risk predictions for the modeled scenarios. All tables and figures follow the text.

Modeling Approach

Conversion of X-38 MSC/NASTRAN model to MSC/DYTRAN

The MSC/NASTRAN model of the X-38 (JSC version: *F062_ed_2.bulk*) was successfully converted to an MSC/DYTRAN model for the nonlinear dynamic impact analysis. This conversion required considerable effort to accurately account for all of the mass and inertial properties, to incorporate material models that allow for nonlinear behavior, and to remesh elements to avoid an extremely small time step.

The MSC/PATRAN software was used as the pre-processor to generate the model. The fuselage modifications were performed with the MSC/NASTRAN Preference since it was more robust and the entire file *F062_ed_2.bulk* could be read into MSC/PATRAN without modification. The impact surface and contact information were generated with the DYTRAN Preference.

In particular, the following modifications were made to *F062_ed_2.bulk*:

<u>Solid Elements</u> - Tetrahedral elements were eliminated to increase the time step. The time step between computations is inversely proportional to the computation time for an explicit solver. Although this modification was relatively minor and involved only elements in the "nose" bulkhead, the resulting increase in time step was approximately two orders of magnitude.

<u>Rigid Body Elements</u> – All rigid body elements were removed as described below.

a) RSPLINE: The aft longitudinal bulkheads (LH Y28 and RH Y28) were remeshed to eliminate the RSPLINE elements at BS = 234. RSPLINE elements do not exist in MSC/DYTRAN. In the revised model, these bulkhead nodes were modified such that the LH Y28 and RH Y28 bulkhead nodes matched up with the nodes on the aft transverse bulkhead stiffeners to which they were attached.

b) RBAR, RBE2: Some RBAR and RBE2 elements were eliminated; others were converted to CBAR elements with very stiff properties.

c) RBE3: All RBE3 cards, which are not supported by MSC/DYTRAN, were eliminated. (See the note regarding lumped mass redistribution under <u>Concentrated Masses</u>.)

<u>Airborne Support Equipment (ASE) Attachment Beam</u> - This beam was remodeled. Offsets and attachments consisting of RBE2 and RBE3 constraints were eliminated, and the beam connectivity was redefined using existing nodes on the forward bulkhead.

<u>PBAR and PBEAM</u>: All neutral axis and shear center offsets were either eliminated, or left as is and ignored by MSC/DYTRAN. MSC/DYTRAN does not allow offsets for beam elements.

<u>PROD</u>: The torsional constant for PROD elements was removed. MSC/DYTRAN does not allow torsional stiffness for PROD elements.

<u>Concentrated Masses</u> - All concentrated masses (CONM2) attached to RBE3 elements were redistributed using a MSC/NASTRAN DMAP to calculate the mass at the independent nodes of all these RBE3 elements. This procedure was not an exact process; however, it can be demonstrated that the total mass is correct. This redistribution tends to lower the center-of-gravity (CG), because some attachment nodes for heavy masses are below the CG of the equipment that they represent. The DMAP process distributes the mass from the CG to the attachment nodes. This effect was partly offset by redefining the RBE3 elements connecting the “stat_balance” masses so that their effective mass would be moved upward.

<u>Crew Masses</u> - There were six crewmembers, each weighing 204 lbs., in the MSC/NASTRAN model. The crew masses in the

MSC/NASTRAN model were connected to the spacecraft with RBE3 elements. These RBE3 elements were eliminated, and the mass of each crewmember was equally distributed over two nodes of the nearest ring frame. Specifically a 0.264 lb s^2/in mass (102 lbs.) was attached to nodes 91035, 91029, 91122, and 91128 at BS91; and to nodes 2452, 2464, 2468, 2379, 7685, 7770, 7766, and 7754 at BS 191. The acceleration responses at these nodes were used as input to the *Dynresp* program to calculate injury risk.

Sandwich Elements - The MSC/NASTRAN model used nonstructural mass (NSM) to represent the combined distributed mass of the panel and the thermal protection system (TPS). Since MSC/DYTRAN ignores the NSM input on PCOMP cards, this mass was redistributed by assigning mass densities to each of the component materials of the sandwich elements.

Static Balance (“Stat_balance”) Masses - Some of the structural attachment beams did not have a mass density assigned to them in the MSC/NASTRAN model. A mass density for each element is required in MSC/DYTRAN, so an appropriate density was assigned based on the material used. Also, some of the rigid elements were replaced with very rigid beam elements, which had to have a mass assigned. These two additional sources of mass were offset in the MSC/DYTRAN model by decreasing the size of the “stat_balance” masses.

Chute Mass and Door – The masses of the main and drogue chutes and the respective chute door were removed since the chutes were assumed to deploy.

Landing Gear and Doors – The landing gear door was removed if the gear operated as designed. For the case where a gear failed to deploy properly, the gear was assumed stowed and the door remained intact.

Material Properties – Although no nonlinear behavior was anticipated, the linear elastic material properties used in the MSC/NASTRAN model were changed to bilinear elastic-plastic to allow calculation of plastic strains in MSC/DYTRAN. The material properties with associated code numbers are listed in Table I.

Impact Surface

The landing (or impact) surface was created using 1,922 solid elements. The material properties of the landing surface were chosen to represent dense sand with a density of 0.000225 lb-s^2/in^4, a Young’s modulus of 11,000 psi, a yield strength of 100 psi, and a hardening modulus of 180 psi. A friction coefficient of 0.8, which was selected by JSC, was used for all three landing simulations.

Landing Gear Model

A rigid model of the X-38 fuselage was created to aid in the development of the MSC/DYTRAN landing gear model and to compare with the DADS landing gear model results (see Appendix). In addition, the DADS model was initially used by LaRC personnel to investigate the forces and motion of the landing gear mechanism. To model the landing gear in MSC/DYTRAN, a user-developed subroutine in FORTRAN was written to simulate the staged honeycomb forces for each gear. Modeling the sliding gear mechanism proved to be difficult. The initial approach, which was unsuccessful, used existing rigid sliding-joint elements (RJCYL and RJTRA) in MSC/DYTRAN to model the gear motion. Following a number of discussions with the code developers, it was determined that the large forces in the landing gear “rigid-joints” were producing instabilities. Consequently, this approach was abandoned. MSC proposed a new approach based on containing the gear motion between four contact surfaces (alignment surfaces) defined by the intersection of two perpendicular shell elements (see Figure 2). This approach, with modifications made by the modeling team, was successful. The large horizontal forces and moments generated by the 0.8 friction coefficient still required adjustments to the contact algorithm to avoid instabilities and high frequency oscillations. Care had to be exercised in specifying several of the MSC/DYTRAN input parameters. The stability of the gear model proved to be particularly sensitive to the thickness of the shell elements and the contact force factor. Deviation of these input values from the defaults was necessary to eliminate ‘chatter’ and unusually large forces at the alignment surfaces.

Coordinate Systems

Three coordinate systems were used in the analysis – global (g), aircraft (a), and seat (s), see Figures 3 and 4. The global (fixed) system was aligned with the x_g-axis horizontal (positive back) and the z_g-axis vertical (gravity-axis positive up). The aircraft axes (x_a, y_a, z_a) were initially aligned with the global axes, but moved with the X-38 model as it rotated and translated. The seats were assumed to be rotated positive 90 degrees about the aircraft y_a-axis with occupant heads aft. Thus, the seat axes used in the injury model have the negative z_s-axis (pelvis-to-head) aligned with the aircraft $+x_a$-axis, and the seat $+x_s$-axis aligned with the $+z_a$-axis. Note the seat coordinate system used for injury calculations is a left-hand system as shown in Figure 4, which was taken from reference 4. In summary, the longitudinal aircraft x_a-accelerations are applied to the occupant primarily along the spine (z_s-axis); whereas, “vertical” aircraft accelerations are primarily applied to the occupant along the back-to-chest direction (x_s-axis).

Dynamic Response Index and Injury Criteria

The MS-DOS PC-program *Dynresp* was used to calculate injury risk probabilities based on DRI (Dynamic Response Index) injury criteria (ref. 4). The program *Dynresp* can also filter the acceleration pulse before applying the injury criteria models. The output from MSC/DYTRAN typically contains high frequency elastic vibrations that mask the primary low-frequency acceleration pulse. Thus, the MSC/DYTRAN predictions were filtered in *Dynresp* with a 4-pole 60 Hz low-pass filter before the DRI was computed. The 60 Hz low-pass filter was recommended in reference 6 for airframe accelerations. All occupants were considered to be healthy. Files that were input into *Dynresp* are listed in the Appendix and are available as electronic ASCII computer files. The program *Dynresp* was run with the following inputs:
“n”,
data file,
description of file,
“h” (meaning healthy),
“I” (read in file and interpolate, file with time, xs,ys,zs-accels),
data file name,

“y” (yes to filter),
“4” (four poles),
“60” (cutoff frequency),
“0.” (starting time),
“0.4” (analysis stop time – note that the DRI maximum can occur after the end of the acceleration pulse),
“0.0001” (sample time interval),
“1” (integration steps per sample interval),
“n” (remove acceleration offsets),
“n” (did ejection seat separation occur).

Simulation Details

Case 1. - No Gears Deployed

The X-38 model with landing gear stowed was placed a very small distance above the impact surface that simulates the landing strip and given initial conditions of -57 ft/s horizontal velocity and –10 ft/s vertical velocity. A friction coefficient of 0.8 between the aircraft and landing surface was requested by JSC for all simulations. The model had a total weight of 22,700 lb. and a center-of-gravity (CG) at x_g= 188 in., y_g= -.09 in., and z_g = 36.9 in. The mass and CG varied slightly for the three cases due to the stow or deployment of gears and the removal of gear doors. The time step for Case 1 was 0.928 microseconds. The impact scenario was essentially over after 60 milliseconds. Approximately 24 hours CPU time on a Sun workstation was required to run the 60 milliseconds of impact simulation. The complexity of the problem is illustrated by the number of solution cycles required. A static elastic problem requires only one solution cycle, while a non-linear static problem may require a dozen or more iterations to converge. For this nonlinear dynamic model, a total of 64,790 solution cycles were required to simulate the 60 millisecond impact scenario.

When the model was post-processed, no material plasticity and only minor deformations were observed. Only three occupant accelerations were analyzed for this case due to symmetry about the x-z plane. The nodes used for the lumped mass occupants were 2464 and 2468 for the two left-of-center back passengers and 91128 for the left forward passenger. A typical acceleration curve from MSC/DYTRAN is shown in Figure 5 for a rear passenger (2464) in the x_s-direction (from back-to-chest). This curve shows high frequency, high amplitude oscillations. This acceleration filtered with a 60-Hz low pass filter is also shown in Figure 5 for comparison. The DRI and injury risk results from the *Dynresp* program are given in Table II for the front and rear passengers. The front passenger locations exhibited the highest acceleration levels and highest risk of injury. The high coefficient of friction tends to produce a large longitudinal deceleration, which since the occupant is seated in a supine position, is along the occupant's spine. The human body is less tolerant to accelerations along the spine than along the seat x_s-axis (back to chest). Without floor and seats, the front passenger's injury risk criteria exceeded both the low risk (1.24) and the moderate risk (1.06) criteria. The back passengers only exceeded the low risk (1.12 and 1.05) criteria.

Case 2. - Nose Gear does not deploy

A rigid body X-38 model constructed in MSC/DYTRAN was used to perform the initial predictions for this case. The rigid body model with a gravity field and the initial conditions of nose gear up, 10 ft/s vertical velocity, and 57 ft/sec horizontal velocity showed that the pitch rotation would not produce nose impact with the contact surface until a time of 195 milliseconds (ms). The rigid body model had functioning landing gear, but all other element material properties were set to RIGID. The rigid body MSC/DYTRAN analysis runs relatively quickly as less than an hour is required for the execution (CPU time). The pitch angle of the aircraft at nose impact was approximately -11 degrees. The total real-time duration for the entire scenario was estimated to be 250 ms. This duration is an extremely long time for an explicit nonlinear dynamic finite element code simulation. To run a fully elastic model for 250 ms would require about 5 1/2 days on the Sun workstation used for the simulations.

Consequently, a two-part simulation was used. The rigid body model with functioning landing gear was run for the first 195 ms. Just prior to nose impact, the x_g-, y_g-, and z_g-locations of all grids and the corresponding velocities were printed out. These initial conditions were then input as the starting point of the elastic model simulation. Problems arose with this approach when it was determined that MSC/DYTRAN would not accept more than 500 unique initial velocity cards. MSC was contacted, and an example user-subroutine was obtained to allow all 20,000 grid point velocities to be input. The approach worked, and the elastic model was run for an additional 60 ms, which required about 24 hours of computer time. The output of the elastic model was then added to the rigid model output starting at 195 ms for a total simulation time of approximately 235 ms. The rigid plus flexible data for the entire landing scenario was then available for input into the injury response program.

Velocity traces in the global coordinate system are shown in Figure 6 for locations at the top of the gear attachment points for each gear. The nose gear attachment point accelerates until nose impact due to the gravitational force. A motion picture analysis of the X-38 pitching over onto its nose is shown in Figure 7. Since all accelerations in MSC/DYTRAN are output in global coordinates, coordinate transformations were necessary to compute the accelerations in the aircraft and seat coordinate system before input into *Dyrespn* to calculate the DRI's and injury criteria. Because of symmetry about the x_a-z_a plane, only three acceleration traces were processed. These accelerations were for the left front passenger at node 91128 and the accelerations for the two left-of-center back passengers at nodes 2464 and 2468. The x_s- and z_s-accelerations in the seat coordinate system for the front passenger at 91128 are shown in Figure 8. The acceleration data for nodes 2464, 2468, and 91128 were input into program *Dyrespn*, and the results are given in Table III. Refer to the Appendix for all seat accelerations.

Case 3. - Starboard Gear does not Deploy

The strategy for this model with a non-deploying starboard gear was the same as for Case 2 where the nose gear did not deploy. The rigid body model with a starboard gear stowed was first run to determine when the starboard side would impact. The starboard side impact occurred at a time of 180 ms with a roll of approximately 11 degrees. The initial conditions from the rigid model at time 180 ms were then input into the elastic MSC/DYTRAN model with the material properties switched from rigid to elastic-plastic. The elastic analysis was run for about 70 ms for a total time of 250 ms. The sequence of pictures shown in Figure 9 illustrate the motion as the aircraft rolls onto its starboard side. Velocity traces in the global coordinate system are shown in Figure 10 for locations at the top of the gear attachment points for each gear. Since there is no symmetry in this impact, accelerations for all six occupants were analyzed. These accelerations were transformed from the global system into the seat system. The acceleration traces from all occupants were input into program *Dyrespn* and the results are given in Table IV.

Injury Risk Predictions

It should be noted that all conclusions presented in this paper are preliminary. From Tables II – IV comparisons can be drawn about the severity of the various landing scenarios based on the MSC/DYTRAN analyses. It is important to note that no seats or floor structure existed in the MSC/NASTRAN model, and thus none could be included in the MSC/DYTRAN model. Therefore, the lumped-mass occupants were assumed rigidly attached to the ring bulkheads at BS 91 and 191. These assumptions limit the scope of the analysis. A friction coefficient of 0.8 was requested by JSC for all runs. This friction coefficient is large compared with an impact on concrete or a runway. Scooping of dirt, which might occur on the dry lakebed near Edwards Air Force Base, was not modeled. Scooping of dirt could make the longitudinal aircraft acceleration (and the spine z_s-acceleration worse). Some newer general aviation aircraft have designs with deflector plates near the nose to prevent the bulkheads from digging into soil (scooping). Seats with energy attenuation along the spine will likely be needed to offset the high accelerations due to the high friction coefficient.

Case 1 – No gears deployed.

This case was the worse impact scenario. In this case, all passengers exceeded the low risk criteria. The front passenger exceeded the moderate risk with a value of 1.06. The back passengers' low risk factors varied from 1.05 to 1.12.

Case 2 – Nose gear did not deploy.

For this case, the front passengers had a low risk factor of 1.16, while the back passengers' risk factor was approximately 1.02.

Case 3 – Starboard gear did not deploy.

This case was the mildest impact scenario. One front passenger exceeded the low risk factor, which was 1.05. The other five passengers had a low risk factor of 1.0 or below.

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5. Stech, E. L.; and Payne, P. R.: "Dynamic Models of the Human Body." AMRL Technical Report 66-157, Wright-Patterson Air Force Base, Ohio, Nov. 1969.

6. Riley, N. E.: "Performance Specification Bag, Impact Attenuation." Specification ZK02033L, General Dynamics, Ft. Worth, TX, September 3, 1985.

Table I. Material properties with associated material identification numbers.

Material number	Density (lb s^2/in^4)	Young's modulus (psi)	Poisson's ratio	Yield strength (psi)	Hardening modulus (psi)
1	.000732	3e7	0.29	85,000	0.1e6
11	.000732	3e7	0.29	85,000	0.1e6
4	.000259	1e7	0.33	62,000	0.18e6
14	.000259	1e7	0.33	62,000	0.18e6
8	.000259	1e7	0.33	62,000	0.18e6
34	.000732	3e7	0.33	62,000	0.1e6
38	.000108	6.36e5	0.30	62,000	0.18e6

Table II - Dynamic Response Model for Injury-Risk Evaluation

Case I - No Gears Deployed

Crew 6- (2468) - back port

data file 2468r9s

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

note - axis system is in seat frame

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	35.33	0.0104	-0.77	0.06	
y-axis	3.47	0.0248	-2.53	0.034	
z-axis	18.66	0.0147	-1.39	0.0553	
Resultant	38.01	0.0108	0	0.0007	
Dynamic Response					
x-axis	15.76	0.0507	-10.24	0.1042	low
y-axis	0.81	0.1281	-1.07	0.0737	low
z-axis	14.45	0.0498	-6.15	0.1128	low
AFGS-87235B Radical	**1.05**	0.0507	0	0.0601	**Exceeds**
Radical	**1.31**	0.1281	0.01	0.3803	**Exceeds**
Radical DRI	14.45	0.049	-7.04	0.1098	
Injury Risk Criteria					
low risk	**1.05**	0.0494	0	0	**Exceeds**
moderate risk	0.89	0.0494	0	0	
high risk	0.72	0.0495	0	0	

Table II - cont. **Crew 5 - (2464)- back center port**

data file 2464r9s

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

note - axis system is in seat frame

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	40.14	0.0111	-20.09	0.0266	
y-axis	5.43	0.0232	-2.76	0.0349	
z-axis	23.83	0.0148	-1.65	0.0569	
Resultant	43.21	0.0115	0	0.0007	
Dynamic Response					
x-axis	15.22	0.0279	-8.91	0.1102	low
y-axis	1.24	0.0414	-0.8	0.0941	low
z-axis	**15.98**	0.05	-6.81	0.1143	**Moderate**
AFGS-87235B Radical	**1.16**	0.0441	0	0.0601	**Exceeds**
Radical	**1.49**	0.0111	0.01	0.3826	**Exceeds**
Radical DRI	15.98	0.05	-7.8	0.1113	
Injury Risk Criteria					
low risk	**1.12**	0.051	0	0	**Exceeds**
moderate risk	0.95	0.0511	0	0	
high risk	0.76	0.0513	0	0	

Table II - cont. **Crew 2 - (91128) - front passengers**

data file 91128r9s

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

note – axis system is in seat frame

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	27.16	0.0309	-15.75	0.0434	
y-axis	7.65	0.0423	-9.12	0.0511	
z-axis	30.18	0.0203	-4.87	0.0442	
Resultant	36.37	0.021	0	0.0007	
Dynamic Response					
x-axis	22.72	0.0446	-13.08	0.0992	low
y-axis	1.5	0.145	-2	0.0906	low
z-axis	**16.16**	0.0465	-6.67	0.1111	**moderate**
AFGS-87235B Radical	**1.07**	0.0511	0	0.0601	**Exceeds**
Radical	**1.28**	0.031	0.01	0.3778	**Exceeds**
Radical DRI	**16.16**	0.0465	-7.63	0.1081	**Exceeds**
Injury Risk Criteria					
low risk	**1.24**	0.0458	0	0	**Exceeds**
moderate risk	**1.06**	0.0458	0	0	**Exceeds**
high risk	0.86	0.0457	0	0	

Table III - Dynamic Response Model for Injury-Risk Evaluation

Case 2 - Nose Gear Not Deployed

Crew 5- (2464) - back center port

data file 2464nupf

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

note - axis system is in seat frame

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	33.59	0.2279	-39.95	0.246	
y-axis	3.61	0.2471	-1.9	0.2248	
z-axis	19.79	0.2171	-0.1	0.1012	
Resultant	40.4	0.246	0.15	0.0009	
Dynamic Response					
x-axis	20.56	0.2428	-20.2	0.2853	low
y-axis	0.95	0.2697	-0.71	0.324	low
z-axis	12.69	0.2462	-5.69	0.3113	low
AFGS-87235B Radical	**1.56**	0.2461	0	0.2501	**exceeds**
Radical	**1.56**	0.2461	0.03	0.4	**exceeds**
Radical DRI	12.59	0.2463	-6.09	0.3084	
Injury Risk Criteria					
low risk	**1.02**	0.2436	0	0	**Exceeds**
moderate risk	0.87	0.2453	0	0	
high risk	0.71	0.2434	0	0	

Table III -cont. **Crew 2 - (91128) - front passengers**

data file 91128nuf

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

note - axis system is in seat frame

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	31.42	0.2065	-14.24	0.25	
y-axis	10.17	0.2142	-6.43	0.2041	
z-axis	33.77	0.2151	-5.82	0.226	
Resultant	38.1	0.2148	0.17	0.0009	
Dynamic Response					
x-axis	24.79	0.2353	-17.19	0.2884	low
y-axis	1.66	0.2388	-1.35	0.2872	low
z-axis	14.27	0.2415	-5.84	0.3078	low
AFGS-87235B Radical	0.96	0.2058	0	0.2501	
Radical	**1.3**	0.2058	0	0.4	**Exceeds**
Radical DRI	14.26	0.2415	-6.68	0.304	
Injury Risk Criteria					
low risk	**1.16**	0.239	0	0	**Exceeds**
moderate risk	1	0.2388	0	0	
high risk	0.82	0.2385	0	0	

Table IV- Dynamic Response Model for Injury-Risk Evaluation

Case 3 - Starboard Gear Not Deployed

Crew 6 - (2468) - back port

data file 2468suf

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

note – axis system is in seat frame

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	6.19	0.2579	-9.69	0.2733	
y-axis	5.19	0.2053	-1.92	0.0159	
z-axis	10.05	0.2092	0.12	0.0009	
Resultant	12.1	0.2082	0.22	0.0009	
Dynamic Response					
x-axis	4.72	0.0593	-3.73	0.295	low
y-axis	6.46	0.2352	-4.34	0.29	low
z-axis	8.25	0.2358	-1.84	0.31	low
AFGS-87235B Radical	0.54	0.24	0	0.28	
Radical	0.62	0.2058	0.01	0.4	
Radical DRI	8.21	0.2359	-2.09	0.3073	
Injury Risk Criteria					
low risk	0.69	0.2355	0	0	
moderate risk	0.56	0.2355	0	0	
high risk	0.42	0.2356	0	0	

Table IV -cont. Crew 5 - (2452)- back center port

data file 2452suf

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

note - axis system is in seat frame

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	15.23	0.2142	-11	0.273	
y-axis	5.18	0.2048	-1.7	0.0159	
z-axis	11.9	0.2095	-0.61	0.229	
Resultant	19.16	0.2134	0.17	0.0009	
Dynamic Response					
x-axis	8.62	0.2321	-8.28	0.2904	low
y-axis	6.65	0.2353	-4.67	0.2904	low
z-axis	9.35	0.2355	-2.97	0.3028	low
AFGS-87235B Radical	0.67	0.2333	0	0.2801	
Radical	0.77	0.2135	0.01	0.3916	
Radical DRI	9.3	0.2356	-3.38	0.2999	
Injury Risk Criteria					
low risk	0.79	0.2346	0	0	
moderate risk	0.65	0.2345	0	0	
high risk	0.5	0.2345	0	0	

Table IV -cont. crew 3 -(7685) - back starboard

data file 7685suf

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	21.55	0.2131	-6.06	0.232	
y-axis	5.81	0.2131	-2.7	0.2756	
z-axis	13.88	0.2078	0.01	0.1515	
Resultant	26.25	0.2131	0.2	0.0009	
Dynamic Response					
x-axis	17.8	0.2315	-11.92	0.2848	low
y-axis	6.42	0.2362	-3.8	0.292	low
z-axis	11.49	0.2366	-3.79	0.303	low
AFGS-87235B Radical	0.77	0.2316	-11.92	0.2801	
Radical	**1.02**	0.2131	-3.8	0.3919	**exceeds**
Radical DRI	11.43	0.2366	-3.79	0.3001	
Injury Risk Criteria					
low risk	1	0.2345	0	0	
moderate risk	0.83	0.2343	0	0	
high risk	0.66	0.234	0	0	

Table IV -cont. **crew 2 -(91122) - front port**

data file 91122suf

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	4.69	0.0864	-7.66	0.2117	
y-axis	12.32	0.2084	-2.09	0.0157	
z-axis	18.22	0.2558	-15.81	0.2375	
Resultant	19.78	0.2126	0.16	0.0009	
Dynamic Response					
x-axis	4.32	0.0602	-5.76	0.2377	low
y-axis	10.84	0.2347	-7.52	0.2891	low
z-axis	11.16	0.2362	-5.46	0.3091	low
AFGS-87235B Radical	**1.32**	0.2375	0	0.2801	**exceeds**
Radical	**1.1**	0.2087	0.01	0.4	**exceeds**
Radical DRI	11.13	0.2362	-6.24	0.3062	
Injury Risk Criteria					
low risk	**1.05**	0.2358	0	0	**exceeds**
moderate risk	0.84	0.2359	0	0	
high risk	0.62	0.236	0	0	

Table IV -cont. **crew 1 -(91035) - front starboard**

data file 91035suf

(Date filtered at 60 Hz (4 pole) in program Dynrespn)

Description	Maximum	Time of Max	Minimum	Time of Min	Risk
Measured Linear Acceleration (G)					
x-axis	4.52	0.0865	-6.21	0.2576	
y-axis	10.76	0.208	-2.22	0.2418	
z-axis	16.16	0.2136	-5.2	0.2342	
Resultant	18.17	0.2123	0.14	0.0009	
Dynamic Response					
x-axis	3.03	0.0609	-2.62	0.1582	low
y-axis	9.53	0.2355	-6.42	0.2895	low
z-axis	10.43	0.2353	-3.65	0.3067	low
AFGS-87235B Radical	0.73	0.2081	0	0.2801	
Radical	0.97	0.208	0	0.3992	
Radical DRI	10.39	0.2353	-4.16	0.3038	
Injury Risk Criteria					
low risk	0.94	0.2353	0	0	
moderate risk	0.75	0.2353	0	0	
high risk	0.56	0.2353	0	0	

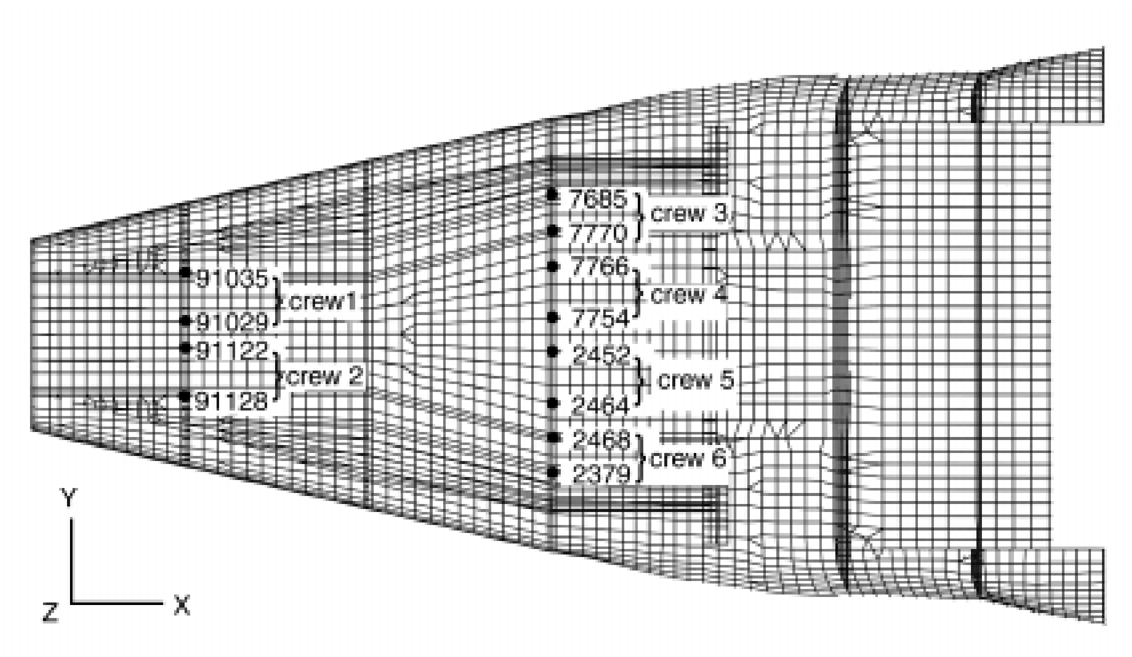


Figure 1. – X-38 MSC/DYTRAN model showing Crew Mass Locations.

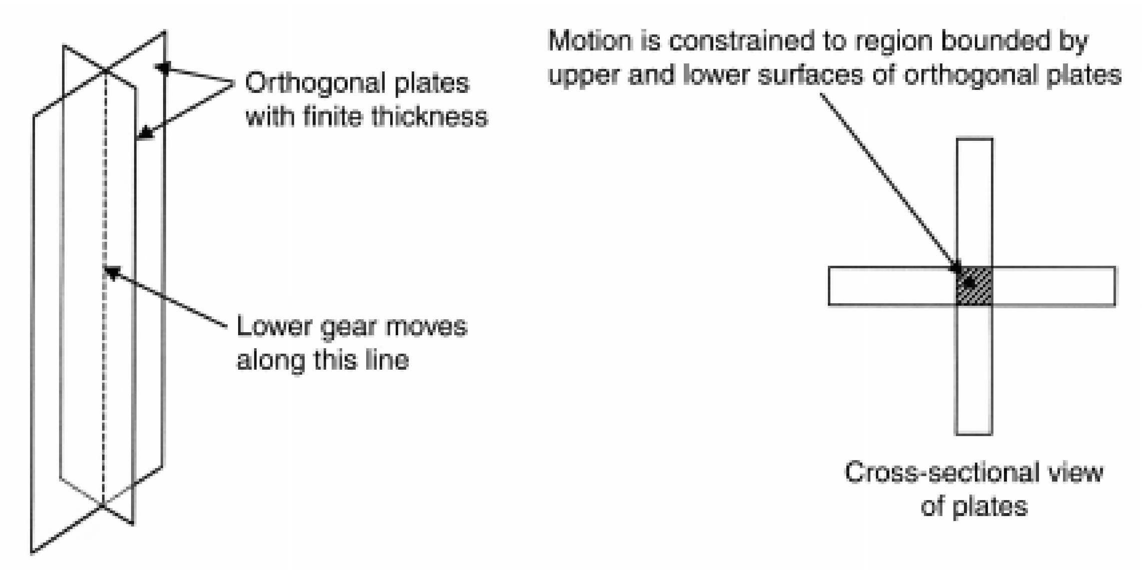


Figure 2. – X-38 MSC/DYTRAN Landing Gear Model.

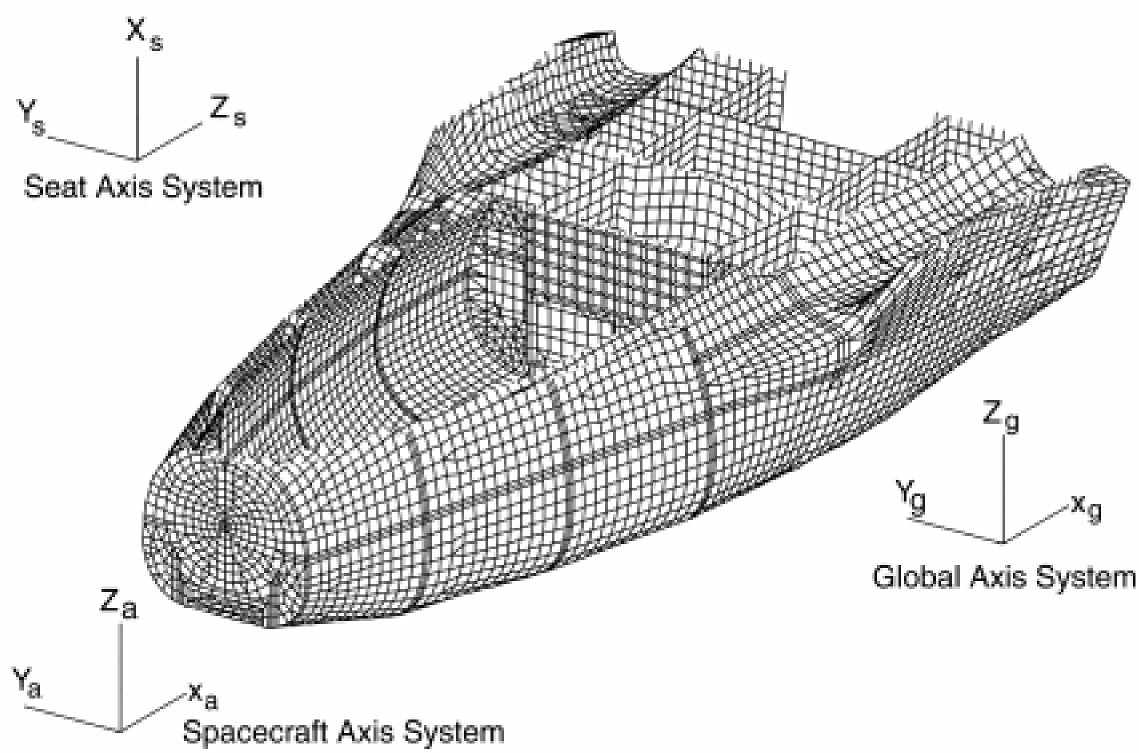


Figure 3. – X-38 axis systems.

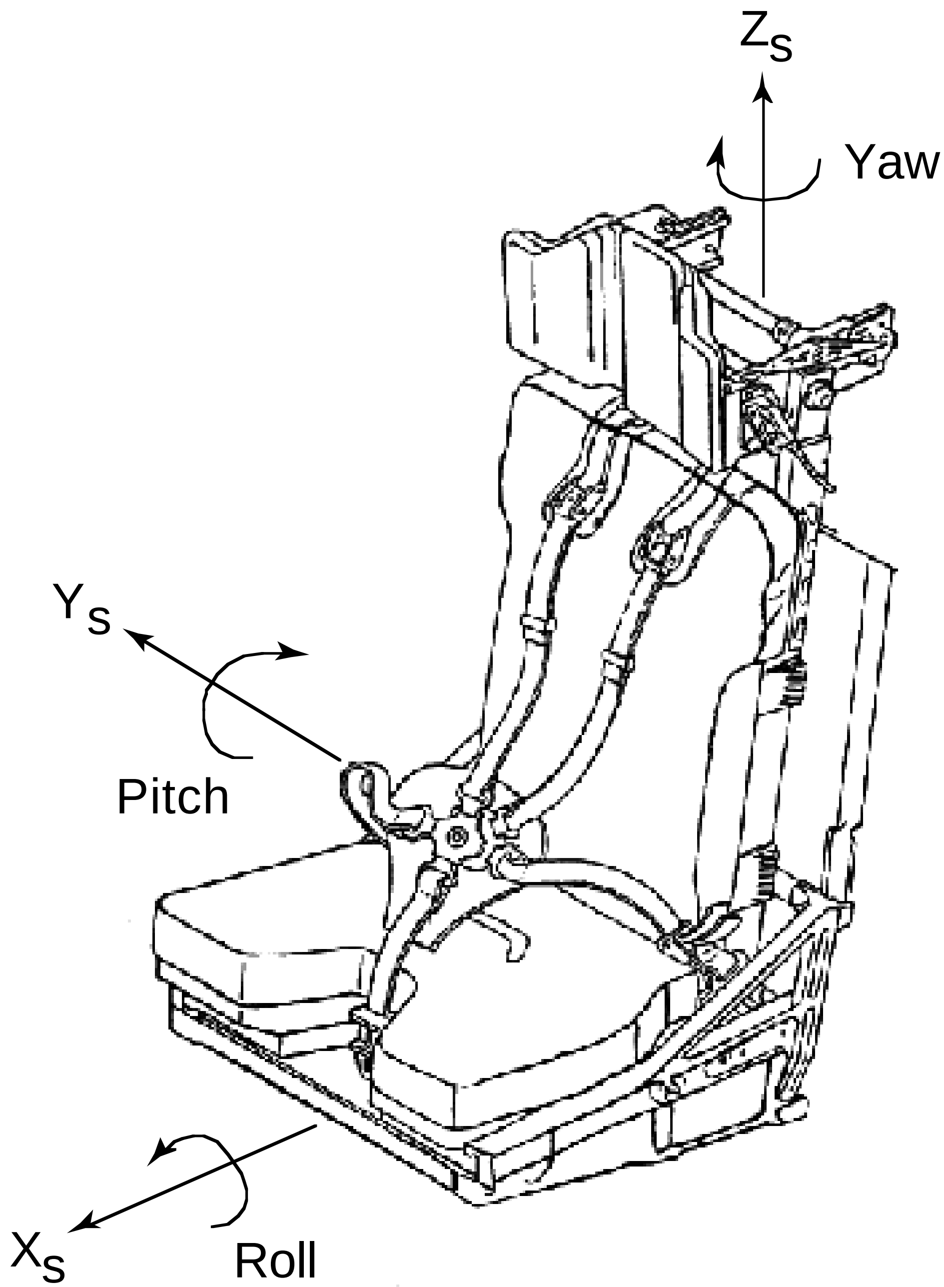


Figure 4. – Seat Coordinate System used for DRI calculations.

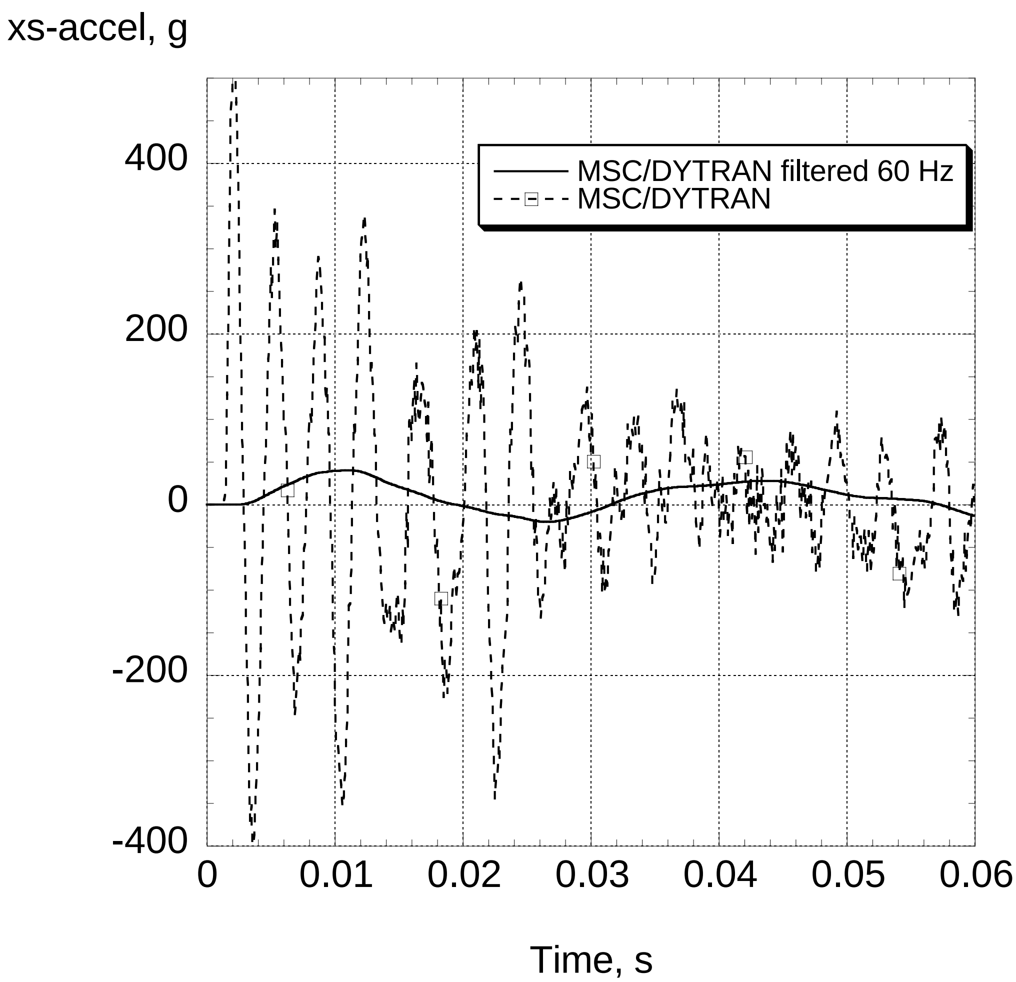


Figure 5. – Rear passenger x_s-acceleration from MSC/DYTRAN unfiltered, and filtered by *Dynrespn* with a low pass 60-Hz filter.

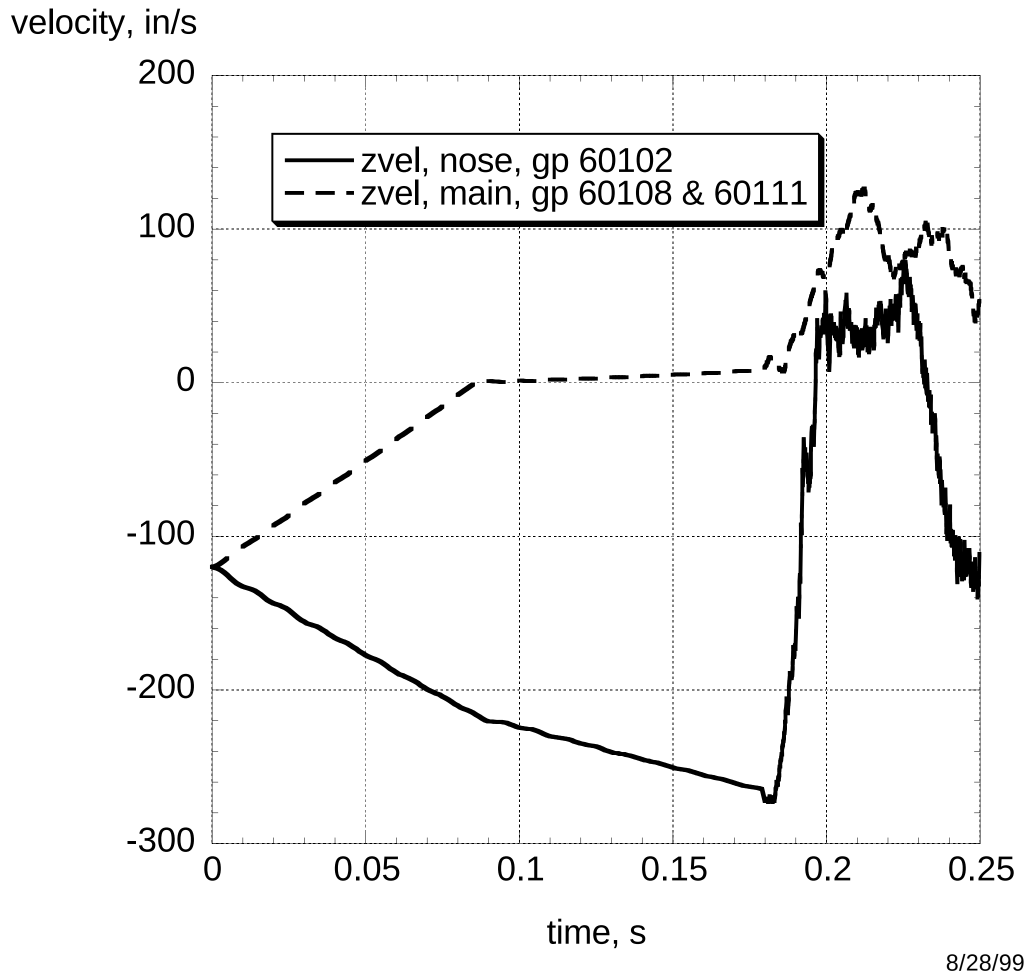


Figure 6. – Global z-velocity for the landing gear attachment points (nose and main) for case 2.

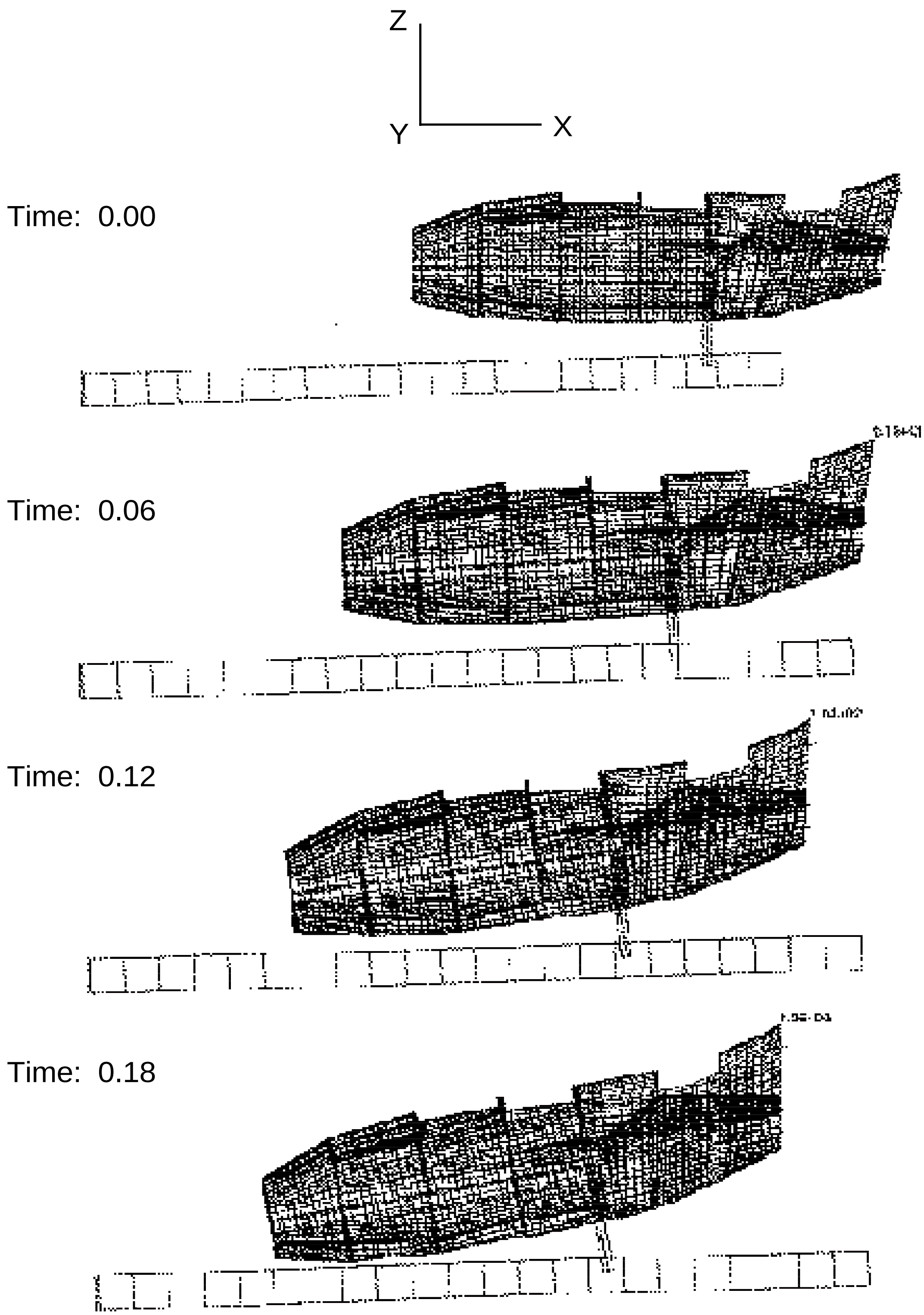


Figure 7. – Plots showing the motion for case 2, nose gear not deployed.

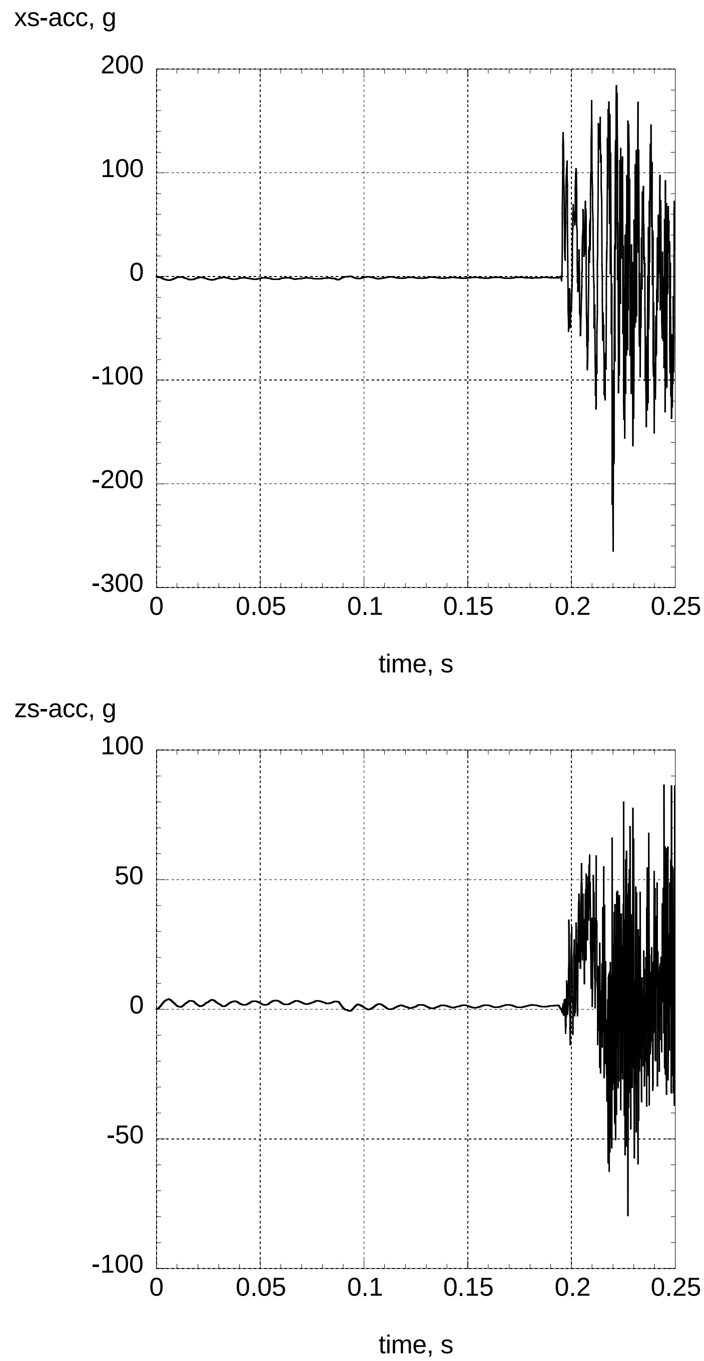


Figure 8. X_s- and z_s-accelerations in the seat axis system of the front crew member on the port side for case 2, nose gear not deployed.

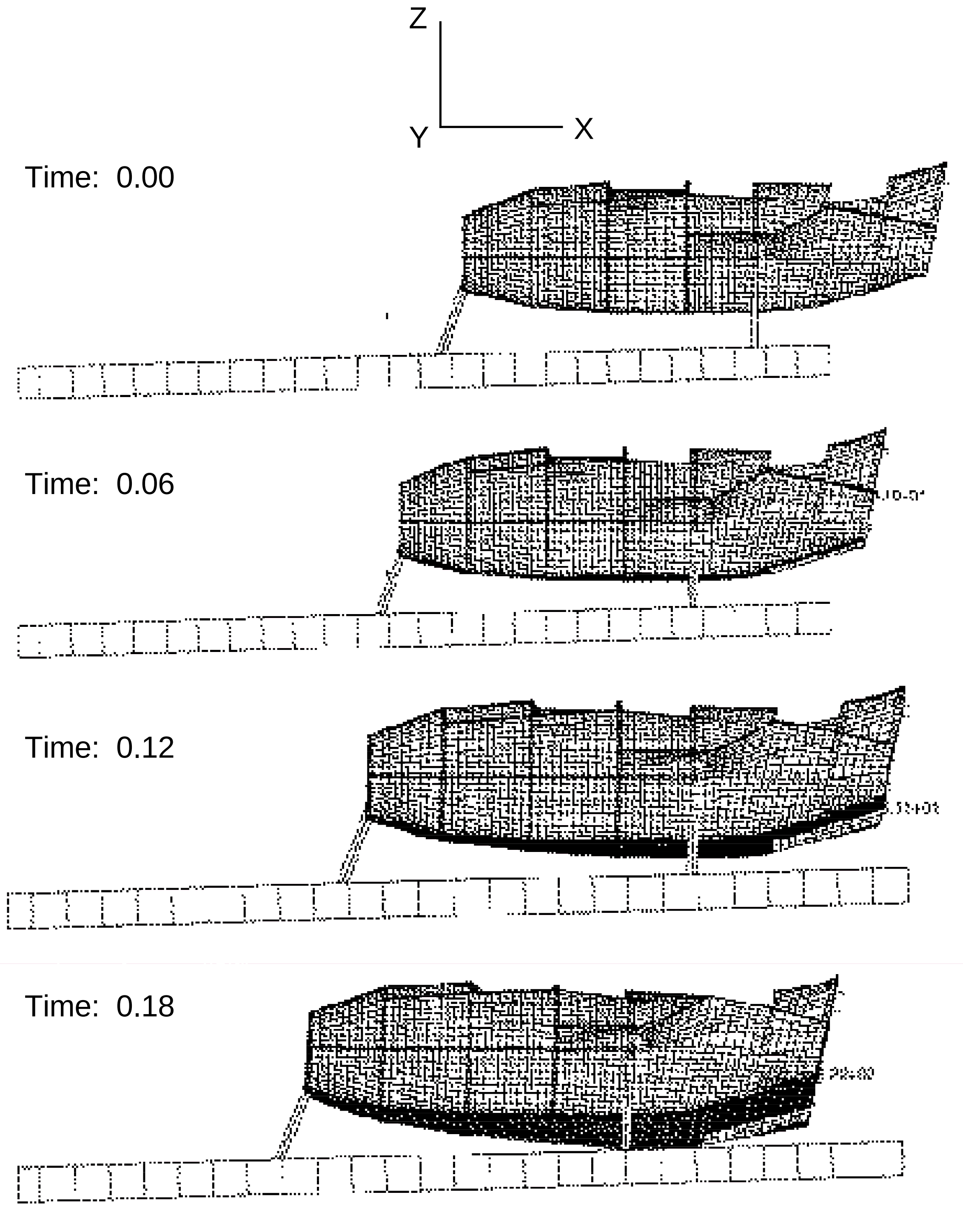


Figure 9. – Plots showing the motion for case 3, starboard gear not deployed.

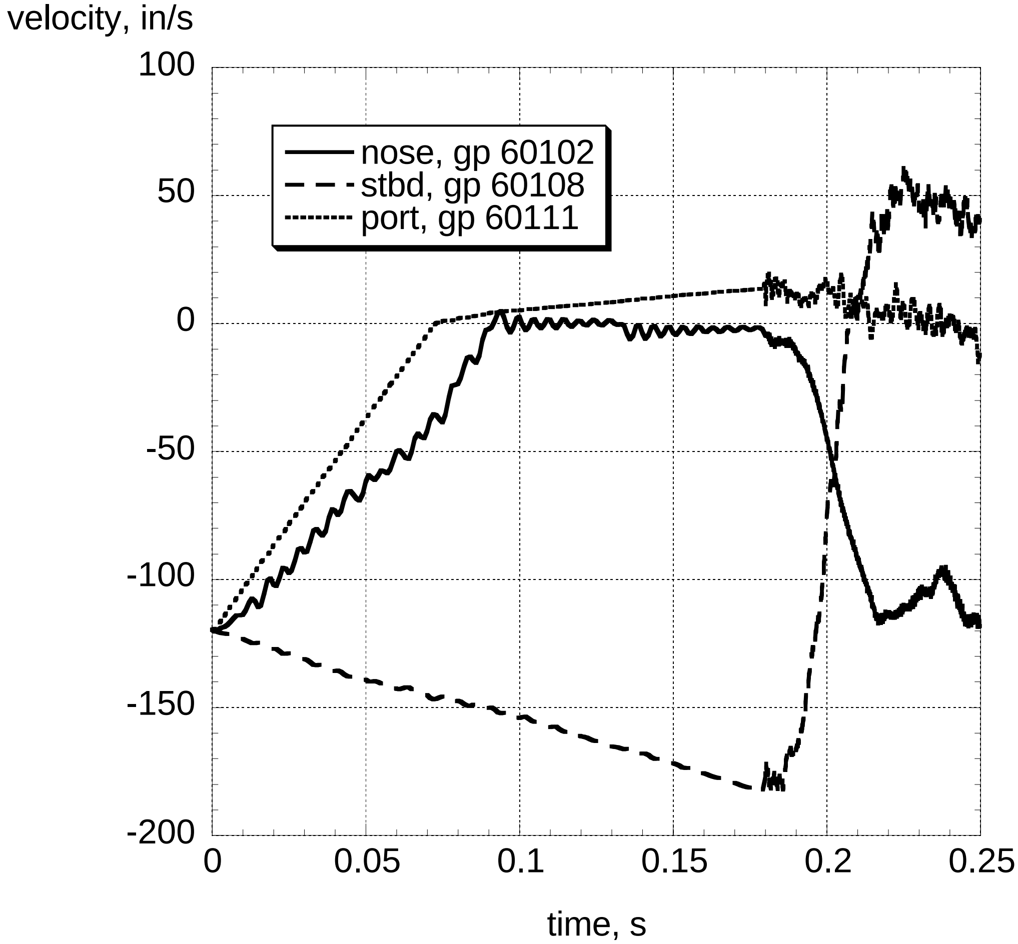


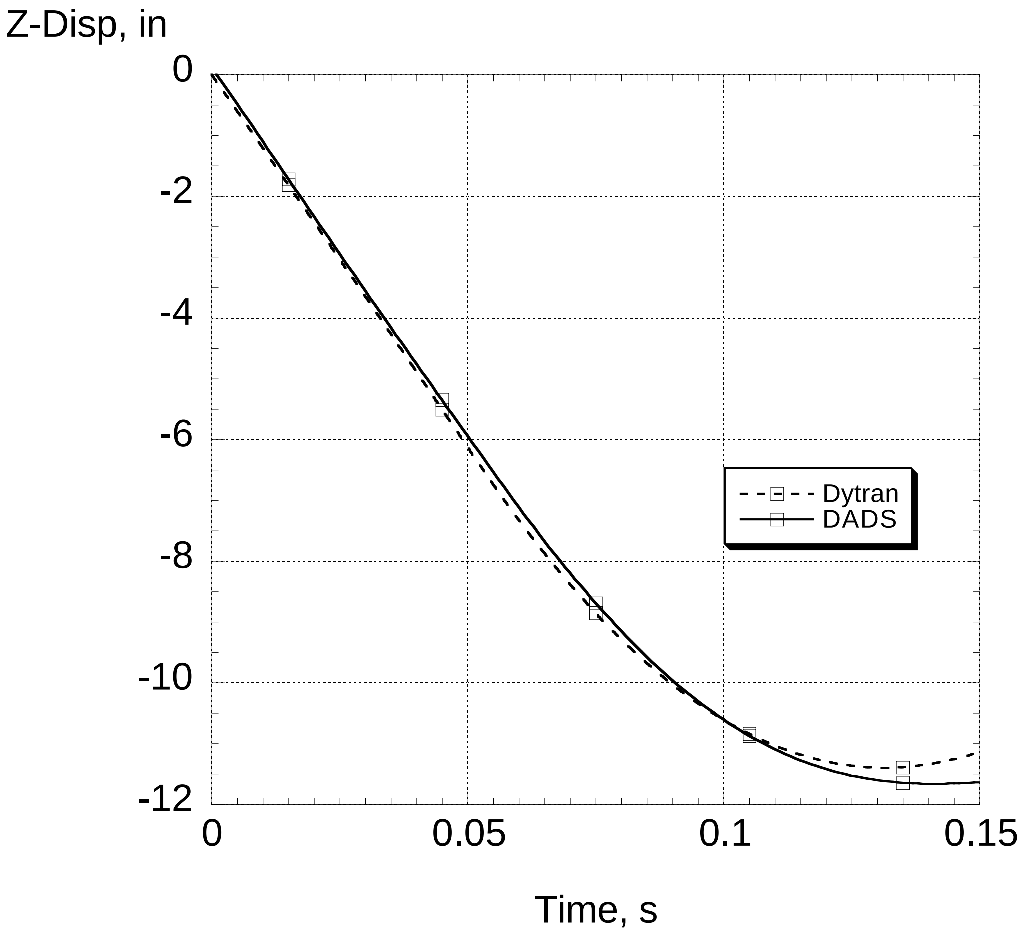
Figure 10. – Elastic model global z-velocities of the landing gear attachement points for case 3, starboard gear not deployed.

Appendix

Comparison of DADS with MSC/DYTRAN

The Dynamic Analysis and Design System (DADS) software is a computer simulation tool used to predict the response of multibody dynamic systems. The DADS model of the X-38 supplied by JSC was instrumental in the development of the nonlinear dynamic finite element model in MSC/DYTRAN. Descriptions of the landing gear model geometry, spring stiffnesses and damping values, mass and inertias that were needed for the DYTRAN model development were taken directly from the DADS model definition file. The DADS subroutine that dictates the ideal plastic compression behavior of the three honeycomb damper elements for the nose and main gear provided information that was duplicated in a MSC/DYTRAN user-subroutine.

A rigid model of the X-38 fuselage was created to aid in the development of the MSC/DYTRAN landing gear model and to compare with the DADS landing gear model results. Several DADS analyses were run and results of vehicle position, velocity, and acceleration, contact forces, gear loads, and gear stroke were plotted so that the DYTRAN model could be validated with the DADS model results. The plot shown below is a comparison of the CG vertical motion from a JSC DADS analysis of the X-38 with 57 ft/s forward velocity and 10 ft/s sink velocity with the MSC/DYTRAN model. The two models show very good agreement.



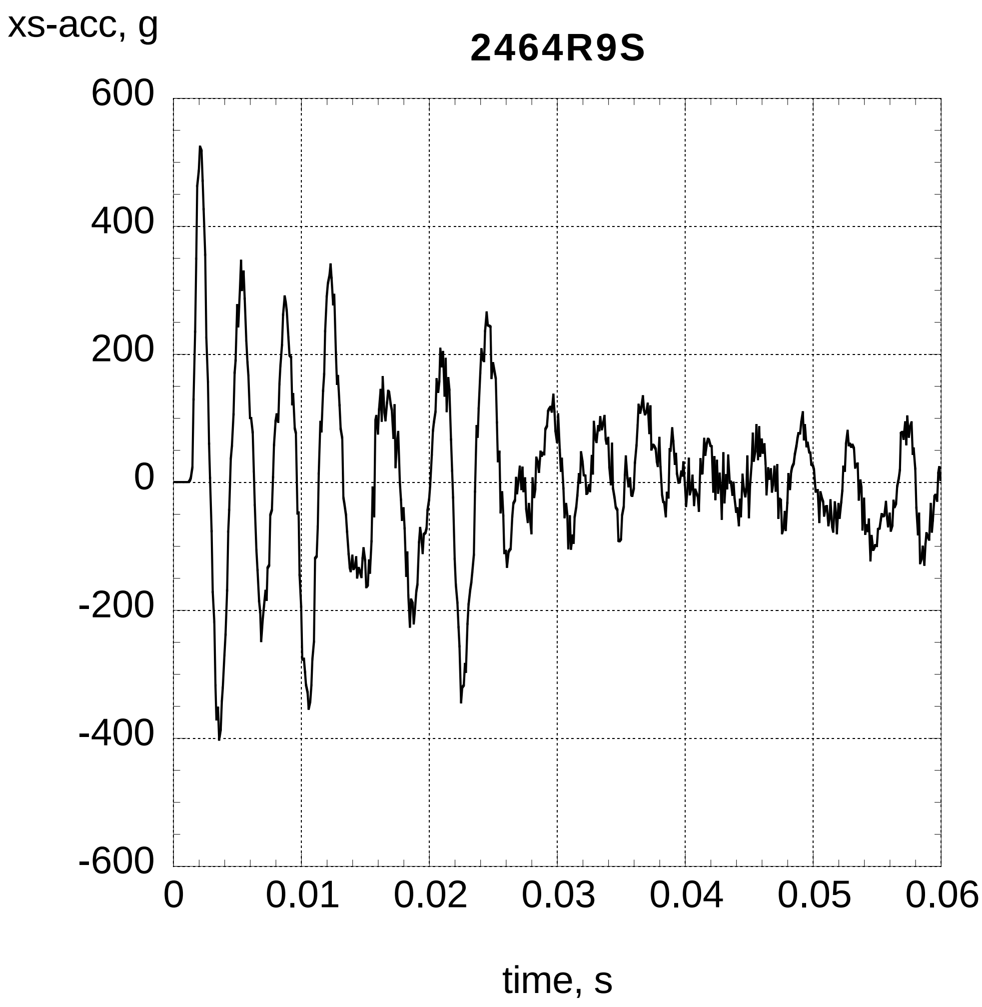
Z-Disp, in
0
-2
-4
-6
-8
-10
-12
0
0.05
0.1
0.15
Time, s
Dytran
DADS

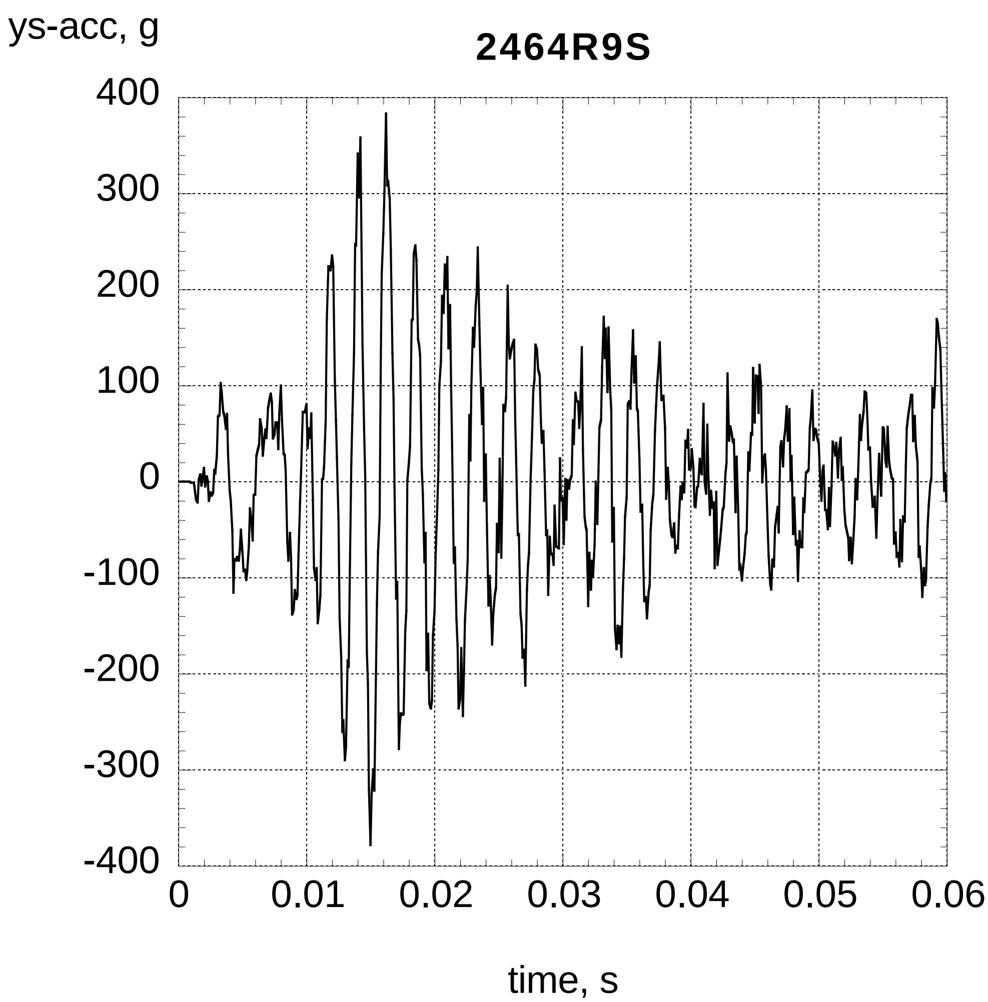
Unfiltered Acceleration Plots

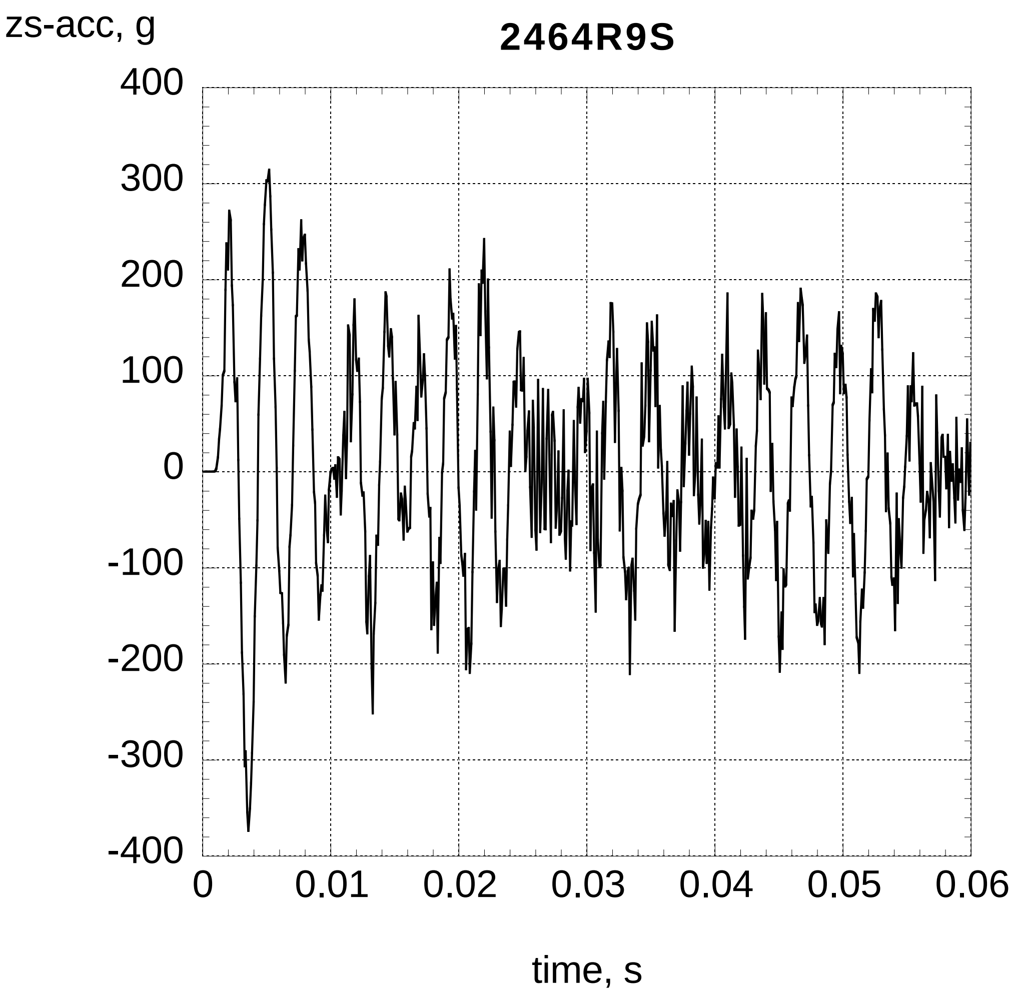
Unfiltered plots of the crew accelerations in the seat reference frame (x_s, y_s, z_s) are shown in this Appendix. These plots were made from the data files used to generate the DRI and injury criteria in Tables II-IV. Each file is in ASCII format with four tab-delimited columns containing acceleration data from MSC/DYTRAN that has been transformed into the seat coordinate system. The first column is time, the second column is the xs-acceleration in g's, the third column is the y_s-acceleration in g's, and the fourth column is the z_s-acceleration in g's. The time step for Case 1 was .0001 seconds. The time step for Case 2 and Case 3 is .001 seconds for the "rigid X-38" part of the analysis, and .0001 seconds for the elastic part of the analysis. The files (labeled on the top of each plot) are available electronically.

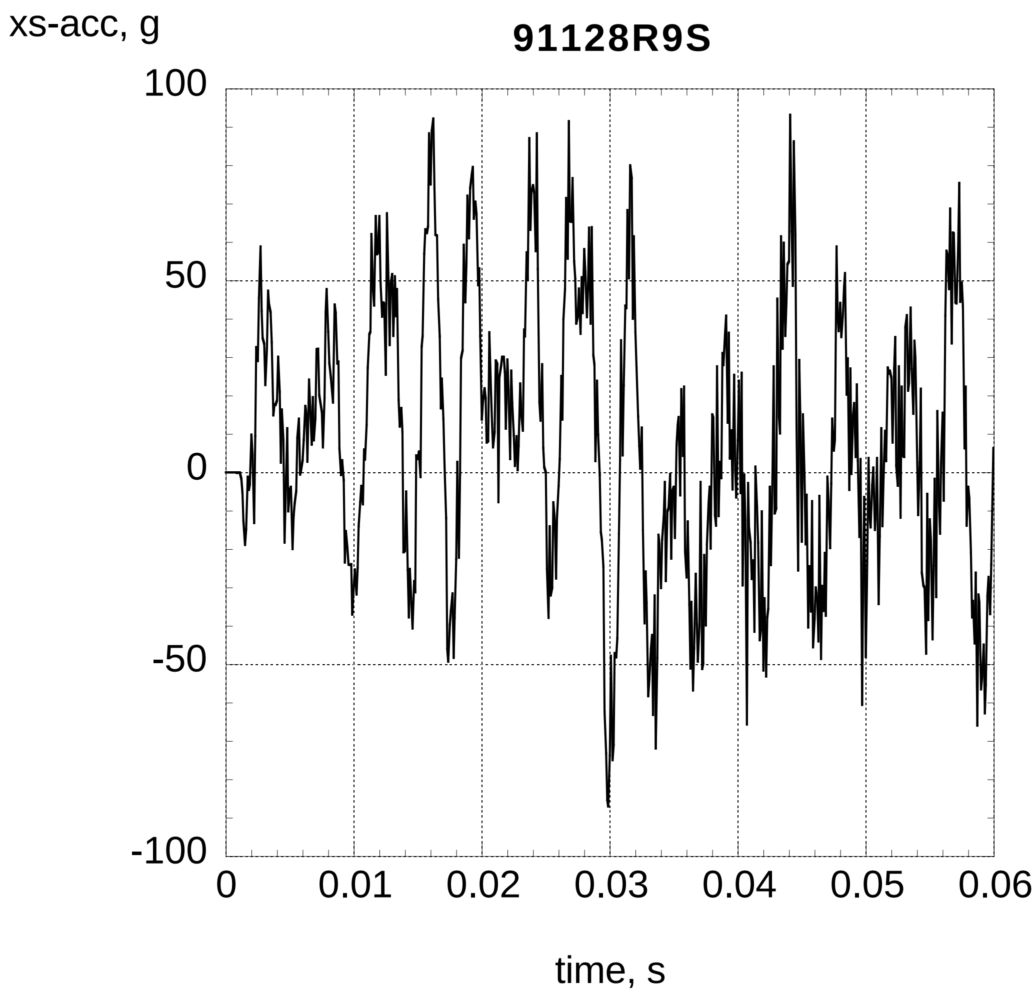
Case 1 – No gears deployed

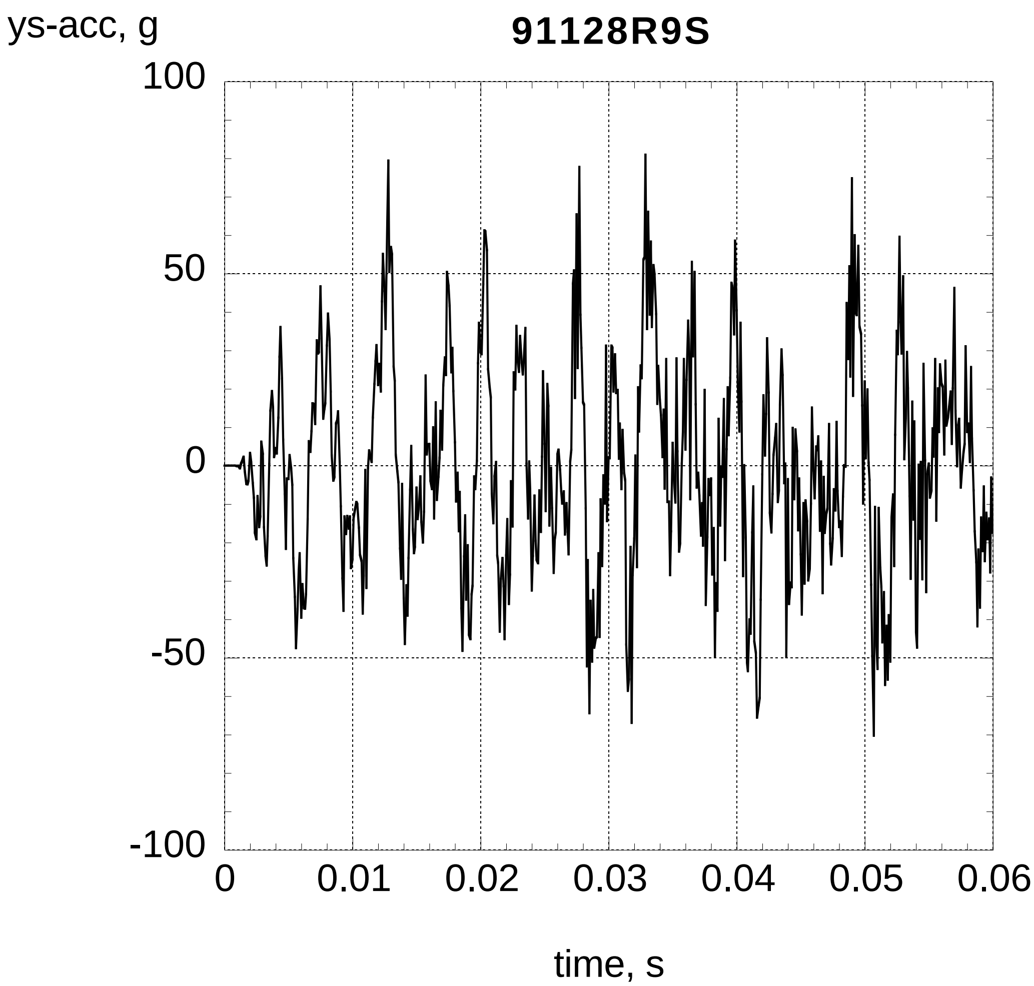
File 2464r9s – crew 5 – back center port
File 91128r9s – crew 2 – front port



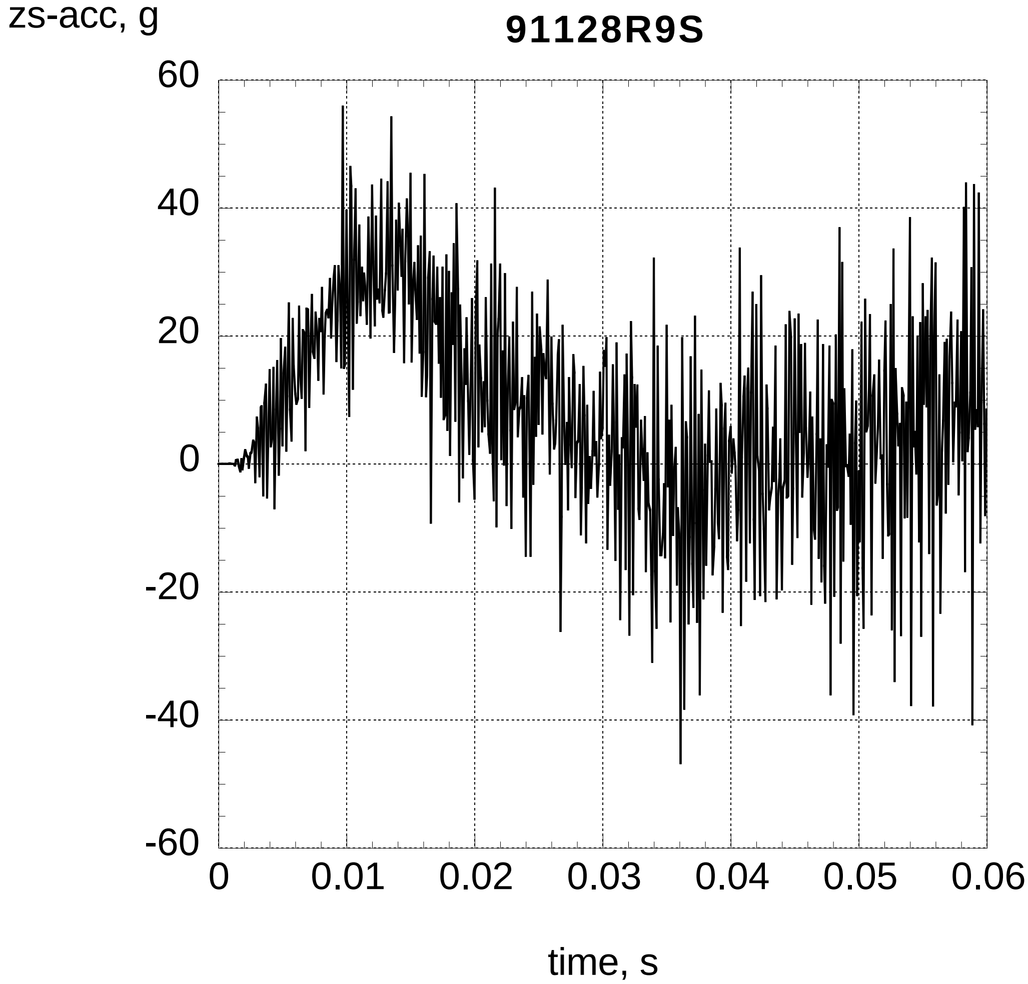

ys-acc, g
2464R9S
400
300
200
100
0
-100
-200
-300
-400
0
0.01
0.02
0.03
0.04
0.05
0.06
time, s


zs-acc, g
2464R9S
400
300
200
100
0
-100
-200
-300
-400
0
0.01
0.02
0.03
0.04
0.05
0.06
time, s


xs-acc, g
91128R9S
100
50
0
-50
-100
0
0.01
0.02
0.03
0.04
0.05
0.06
time, s

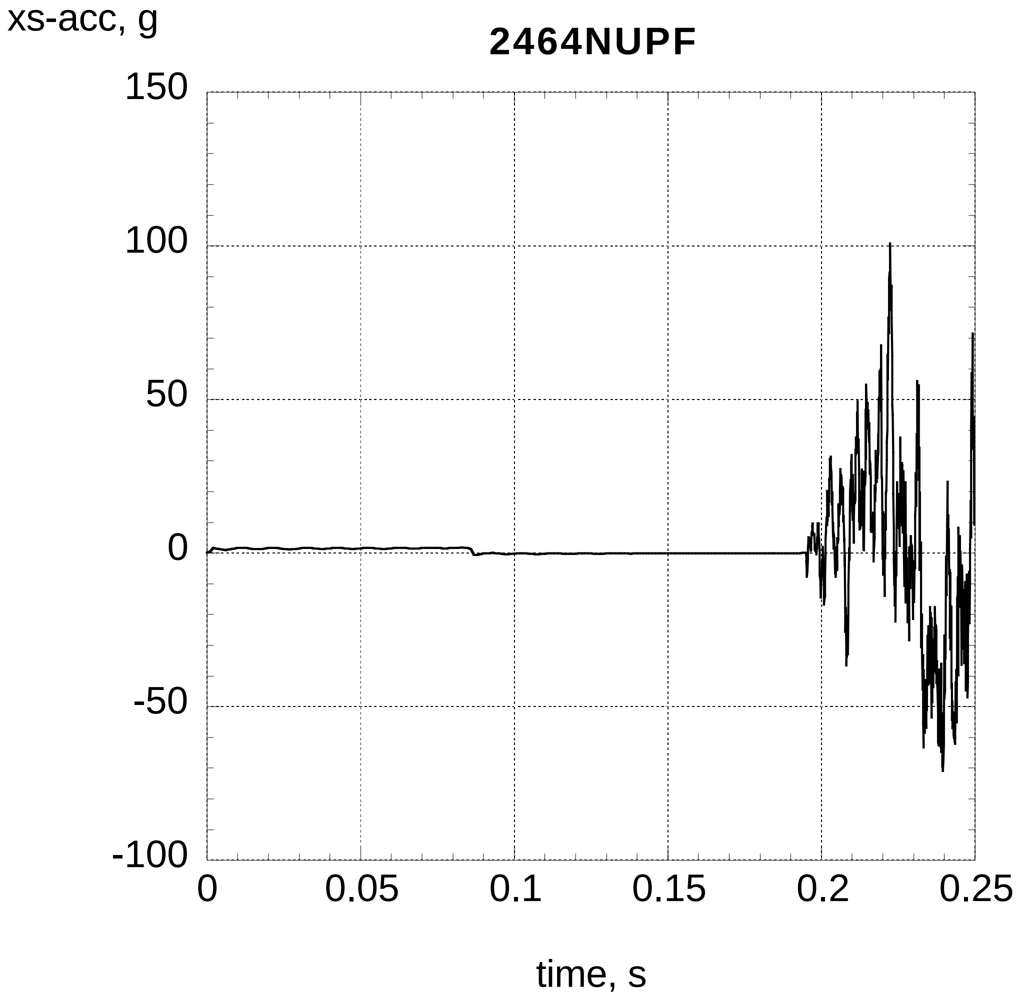


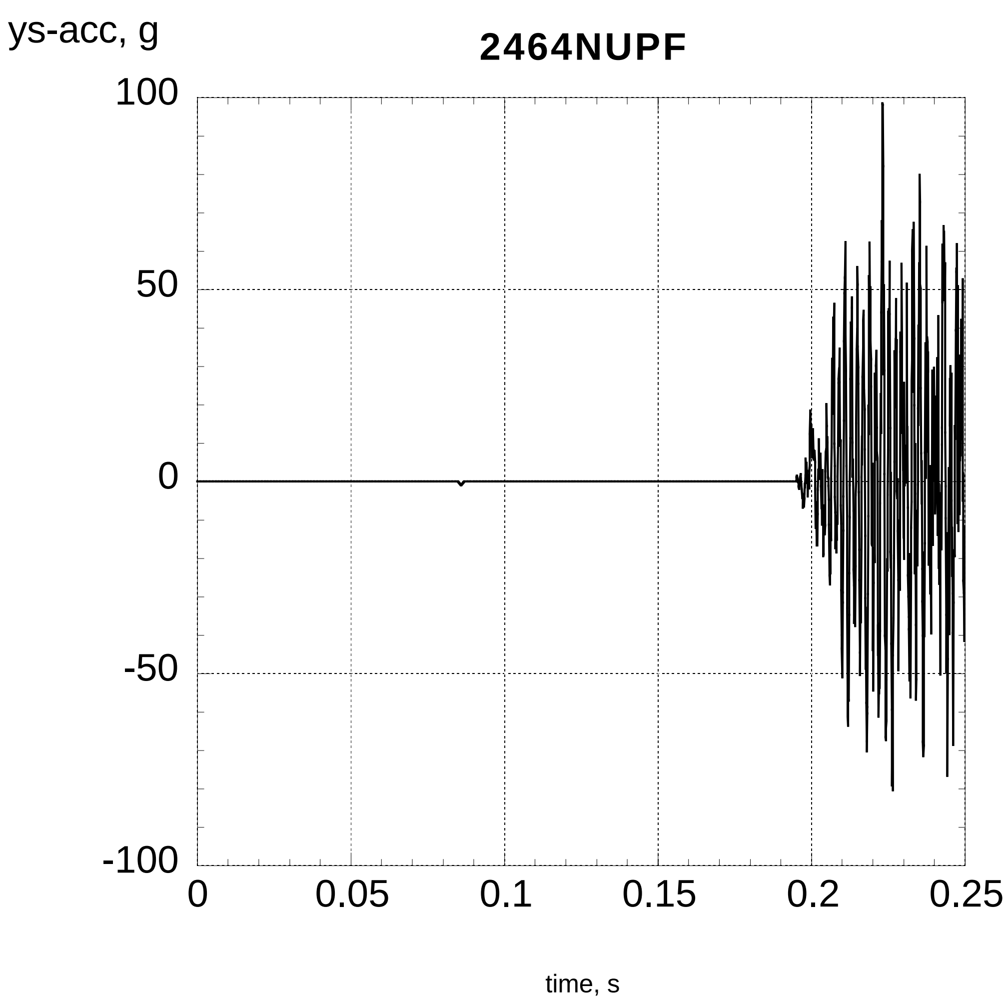
ys-acc, g
91128R9S
100
50
0
-50
-100
0
0.01
0.02
0.03
0.04
0.05
0.06
time, s

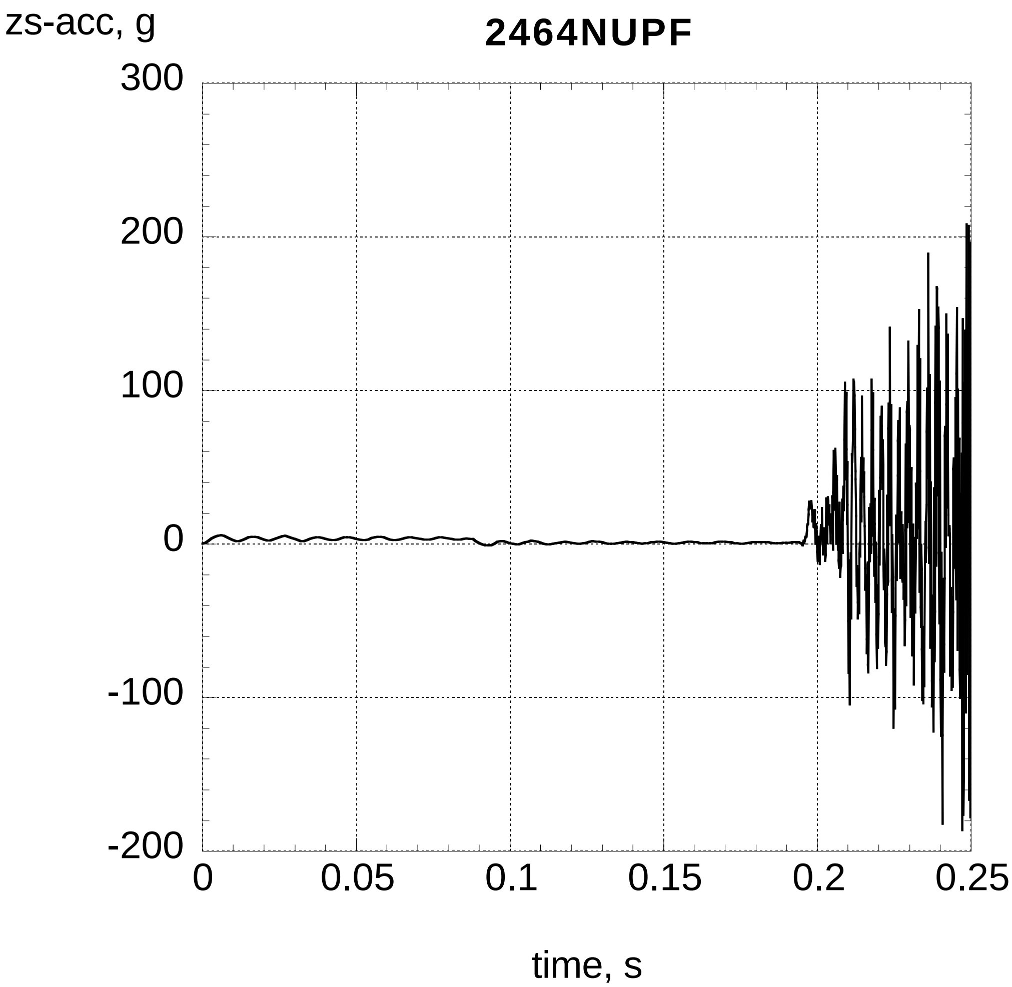

zs-acc, g
91128R9S
60
40
20
0
-20
-40
-60
0
0.01
0.02
0.03
0.04
0.05
0.06
time, s

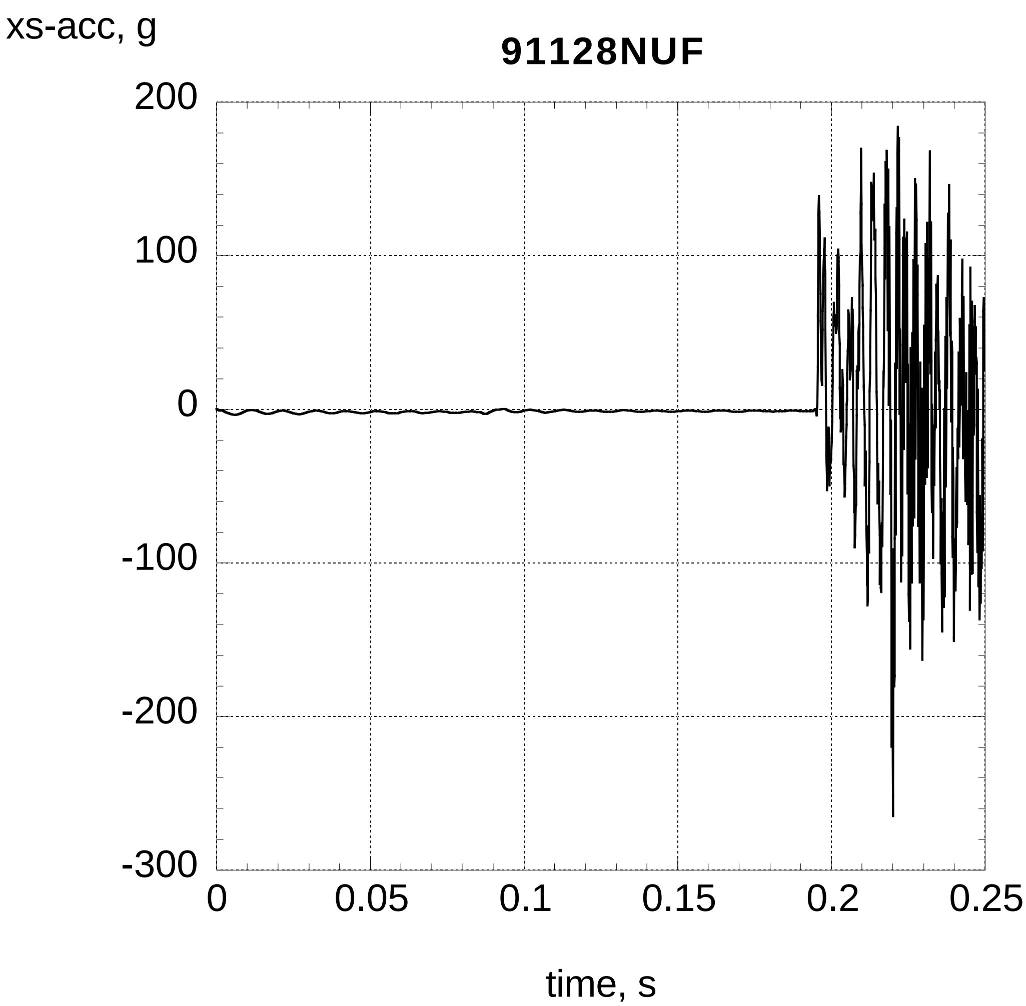
Case 2 – Nose gear not deployed

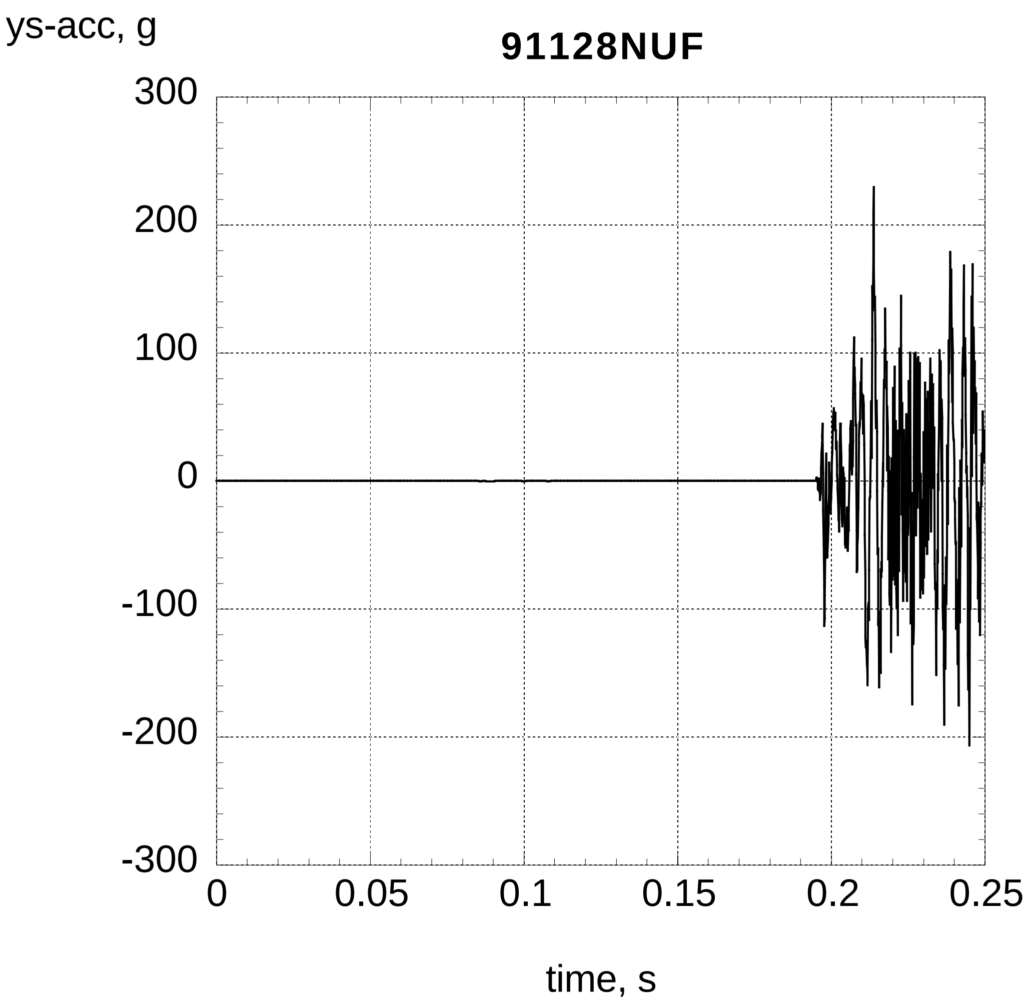
File 2464nupf – crew 5 – back center port
File 91128nuf – crew 2 – front port

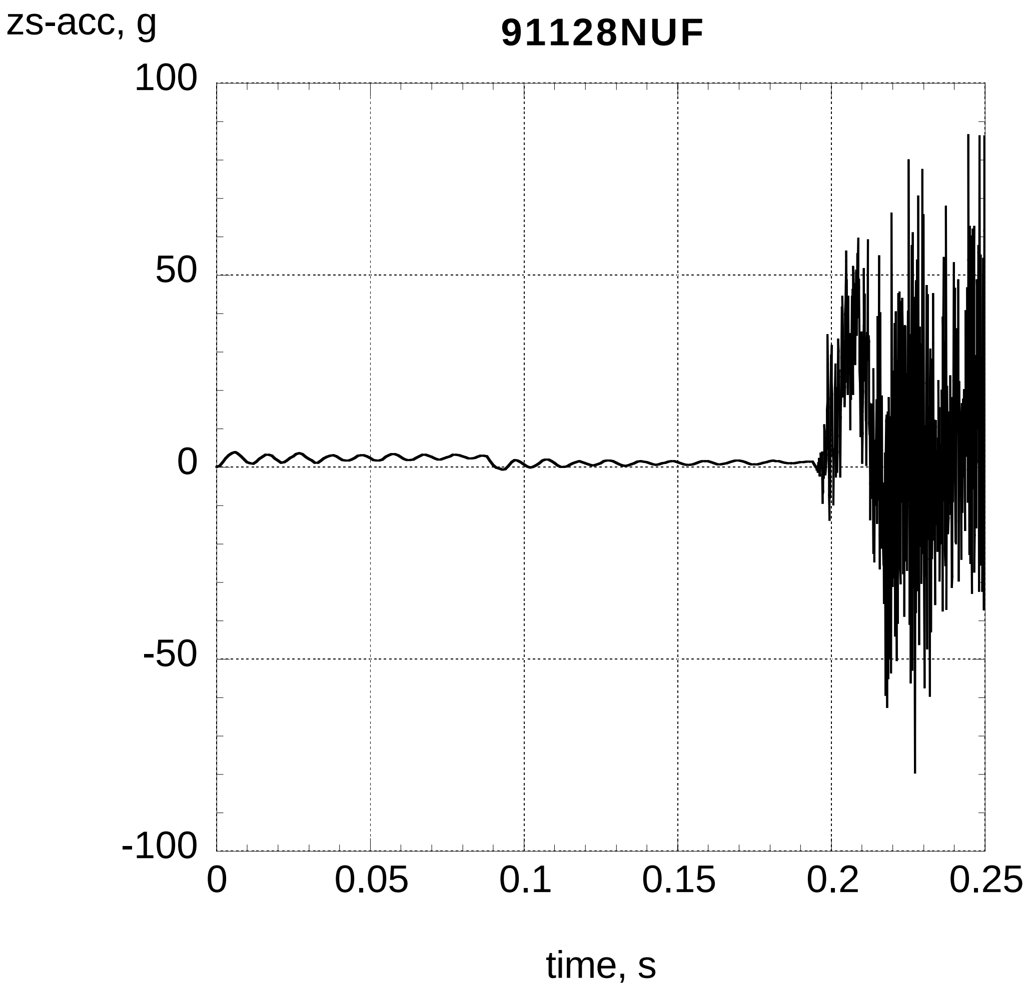

xs-acc, g
2464NUPF
150
100
50
0
-50
-100
0
0.05
0.1
0.15
0.2
0.25
time, s


ys-acc, g
2464NUPF
100
50
0
-50
-100
0
0.05
0.1
0.15
0.2
0.25
time, s


zs-acc, g
2464NUPF
300
200
100
0
-100
-200
0
0.05
0.1
0.15
0.2
0.25
time, s

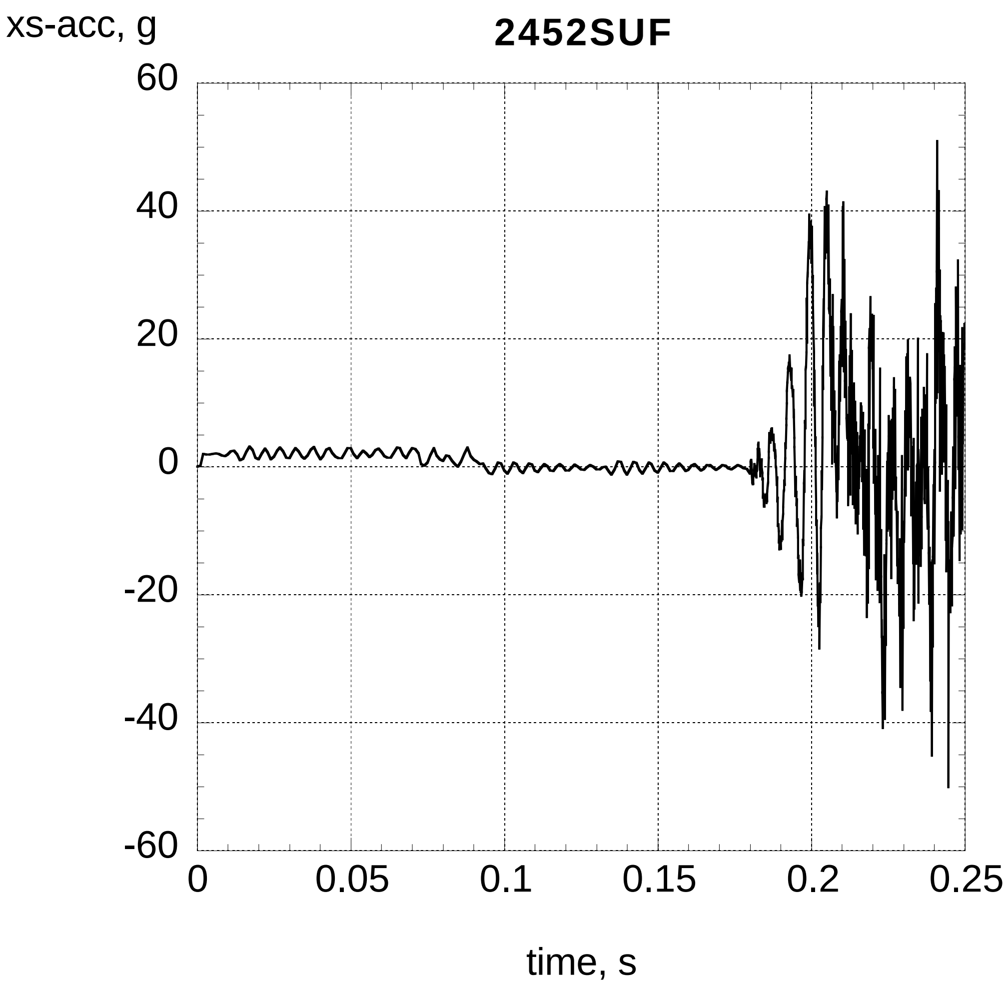

xs-acc, g
91128NUF
200
100
0
-100
-200
-300
0
0.05
0.1
0.15
0.2
0.25
time, s

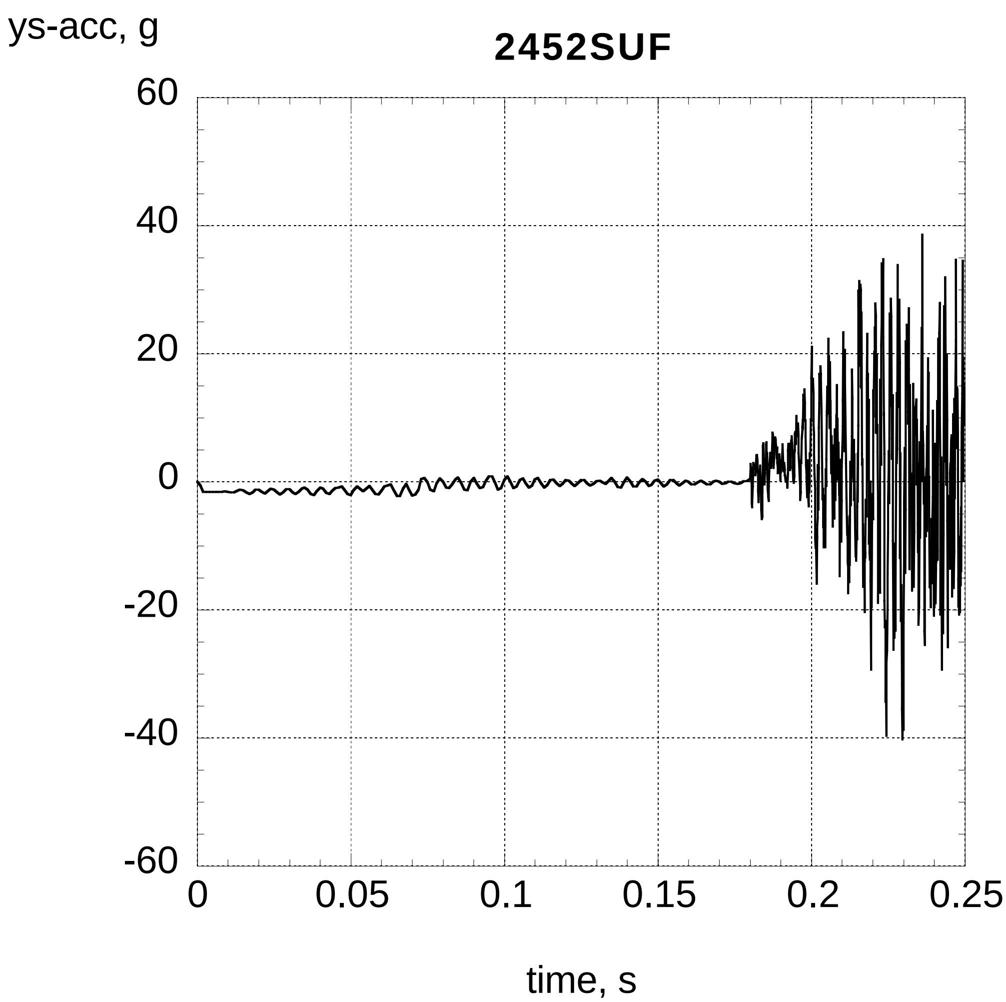

ys-acc, g
91128NUF
300
200
100
0
-100
-200
-300
0
0.05
0.1
0.15
0.2
0.25
time, s


zs-acc, g
91128NUF
100
50
0
-50
-100
0
0.05
0.1
0.15
0.2
0.25
time, s

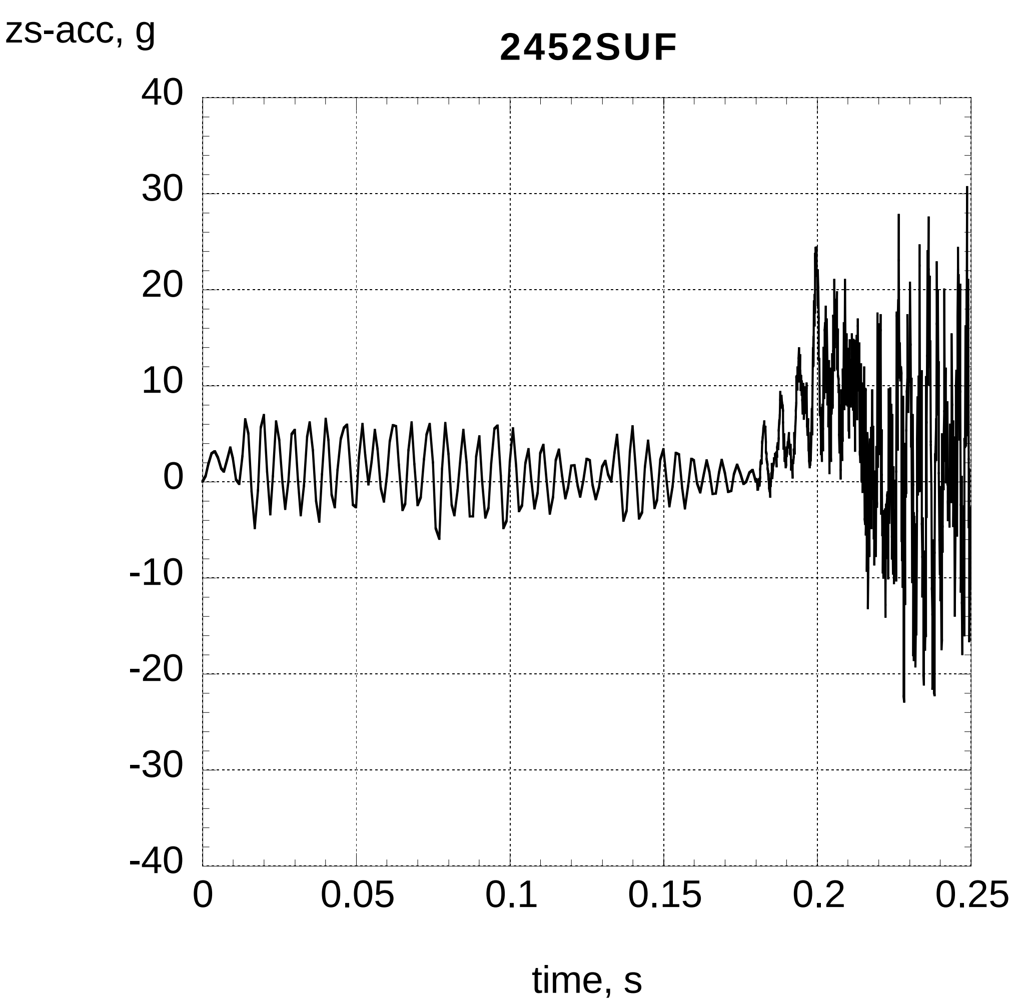
Case 3 – Starboard gear not deployed

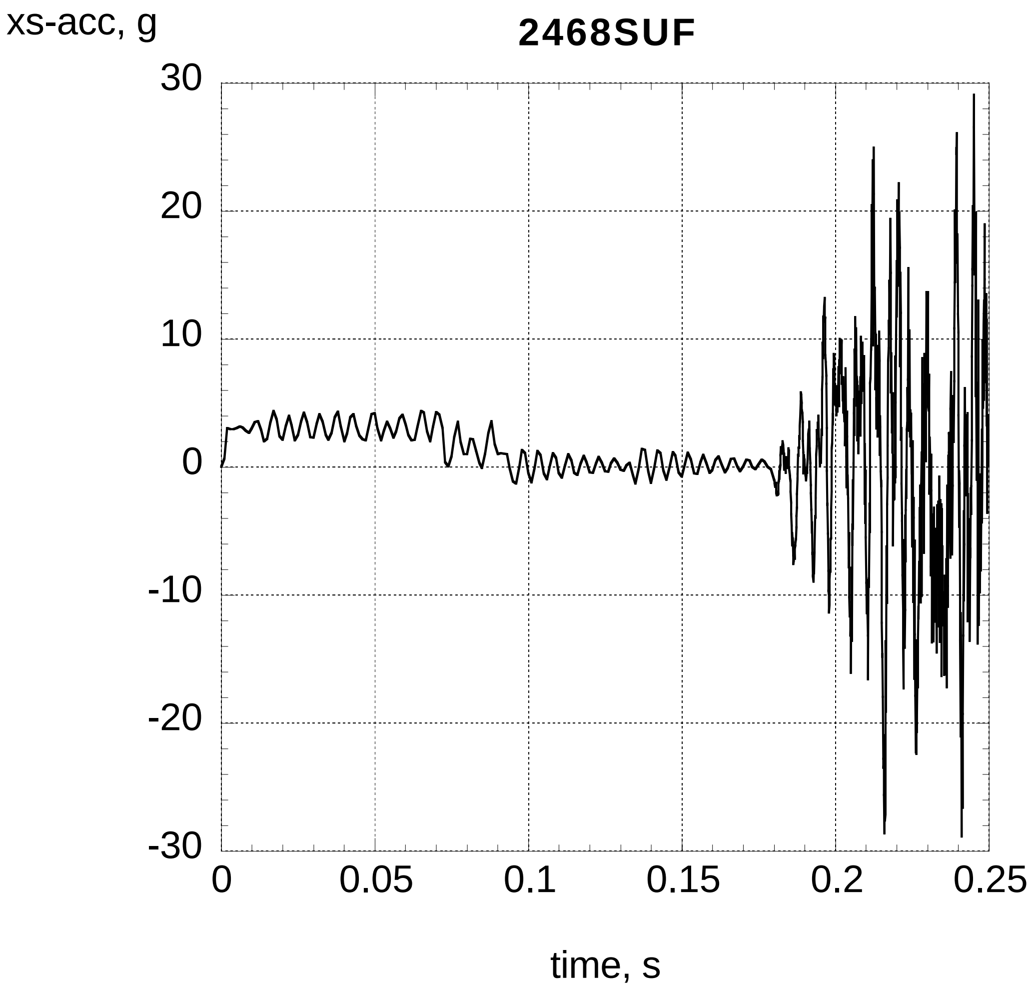
File 2452suf – crew 5 –back center port
File 2468suf – crew 6 – back port
File 7685suf – crew 3 – back starboard
File 7754suf – crew 4 –back center starboard
File 91035suf – crew 1 – front starboard
File 91022suf – crew 2 – front port

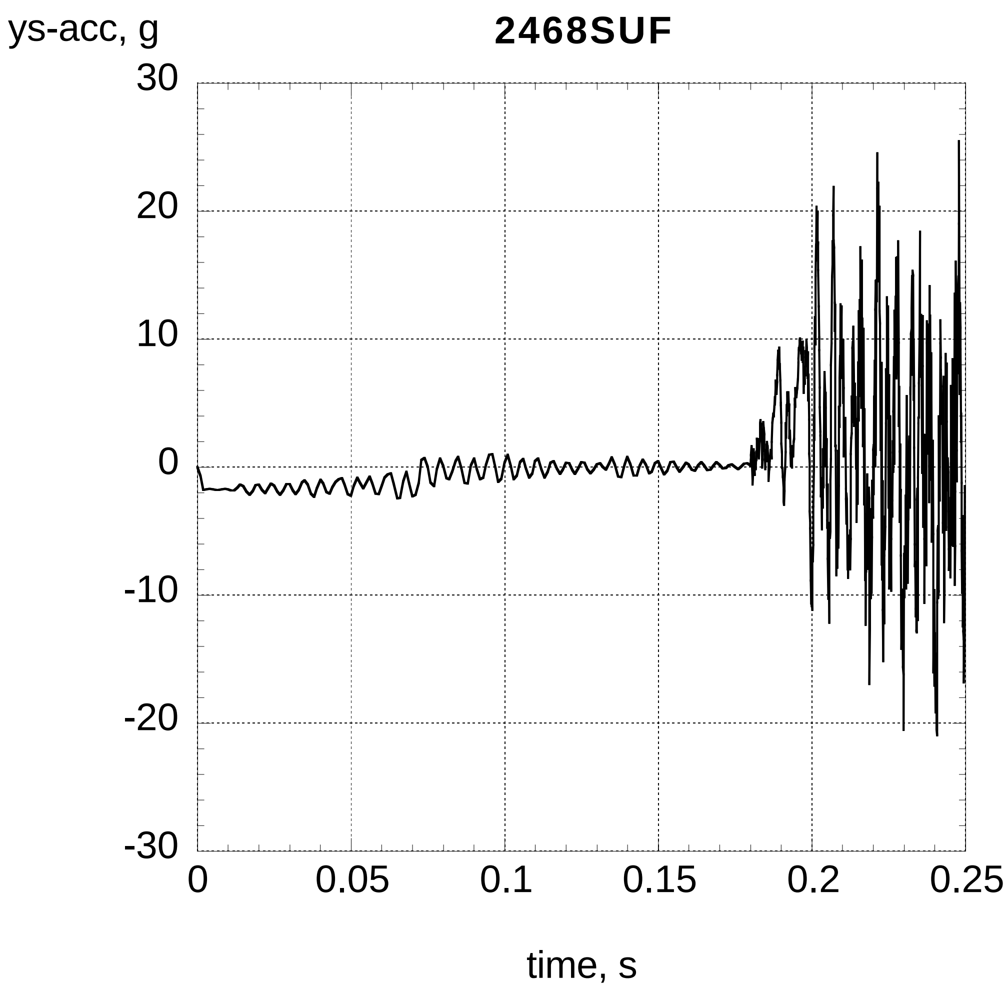

xs-acc, g
2452SUF
60
40
20
0
-20
-40
-60
0
0.05
0.1
0.15
0.2
0.25
time, s

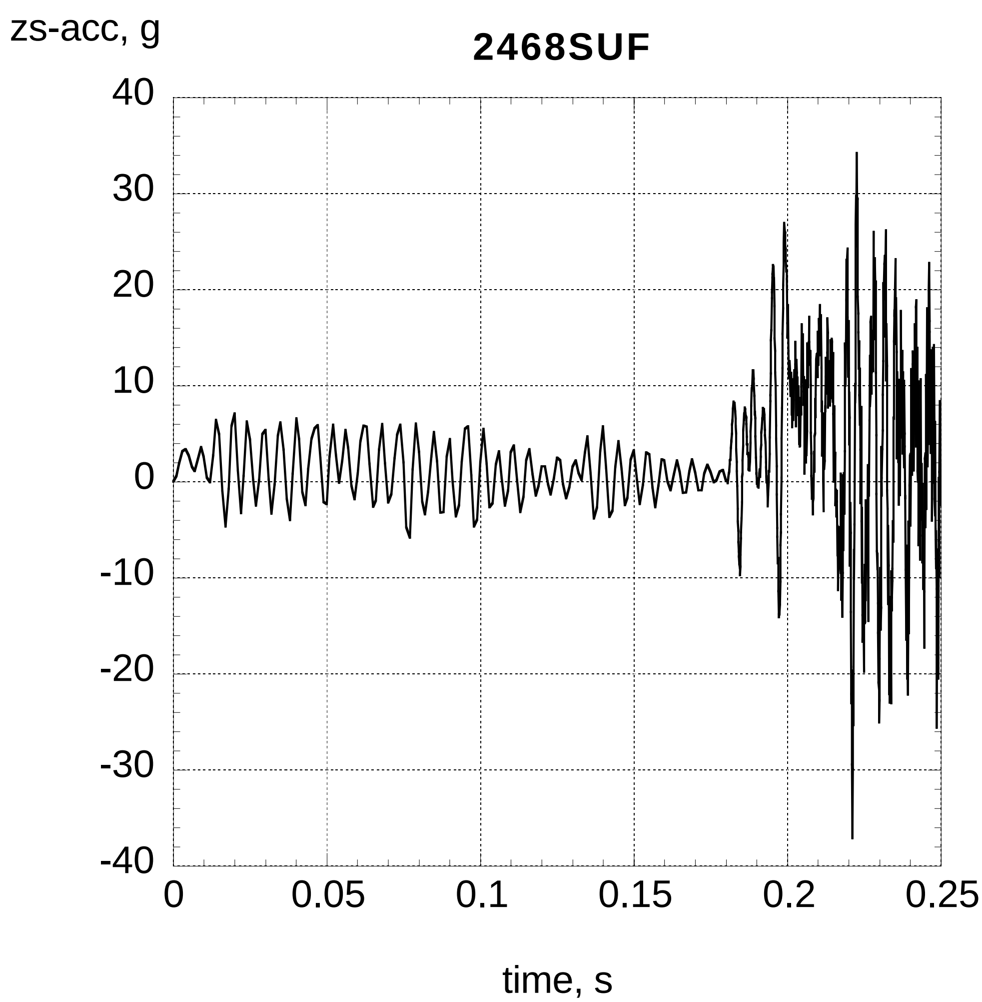


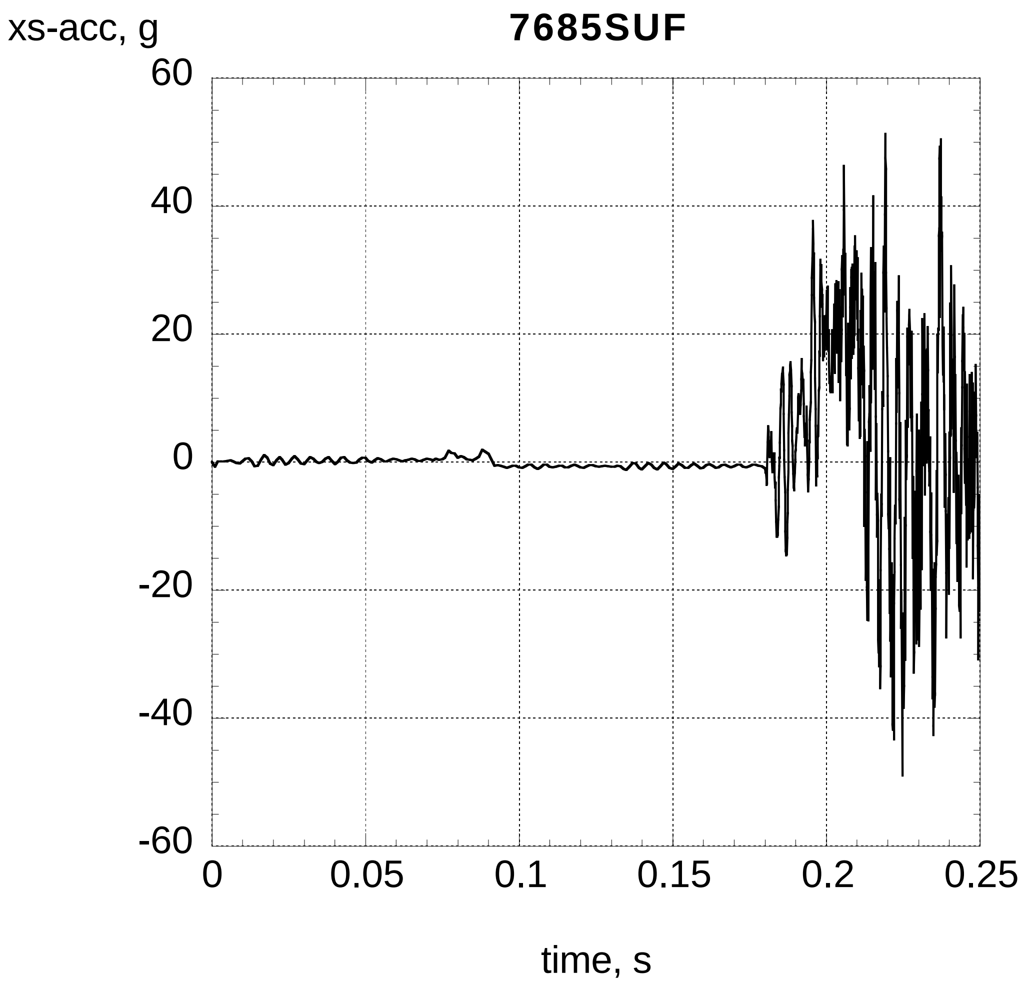
ys-acc, g
2452SUF
60
40
20
0
-20
-40
-60
0
0.05
0.1
0.15
0.2
0.25
time, s

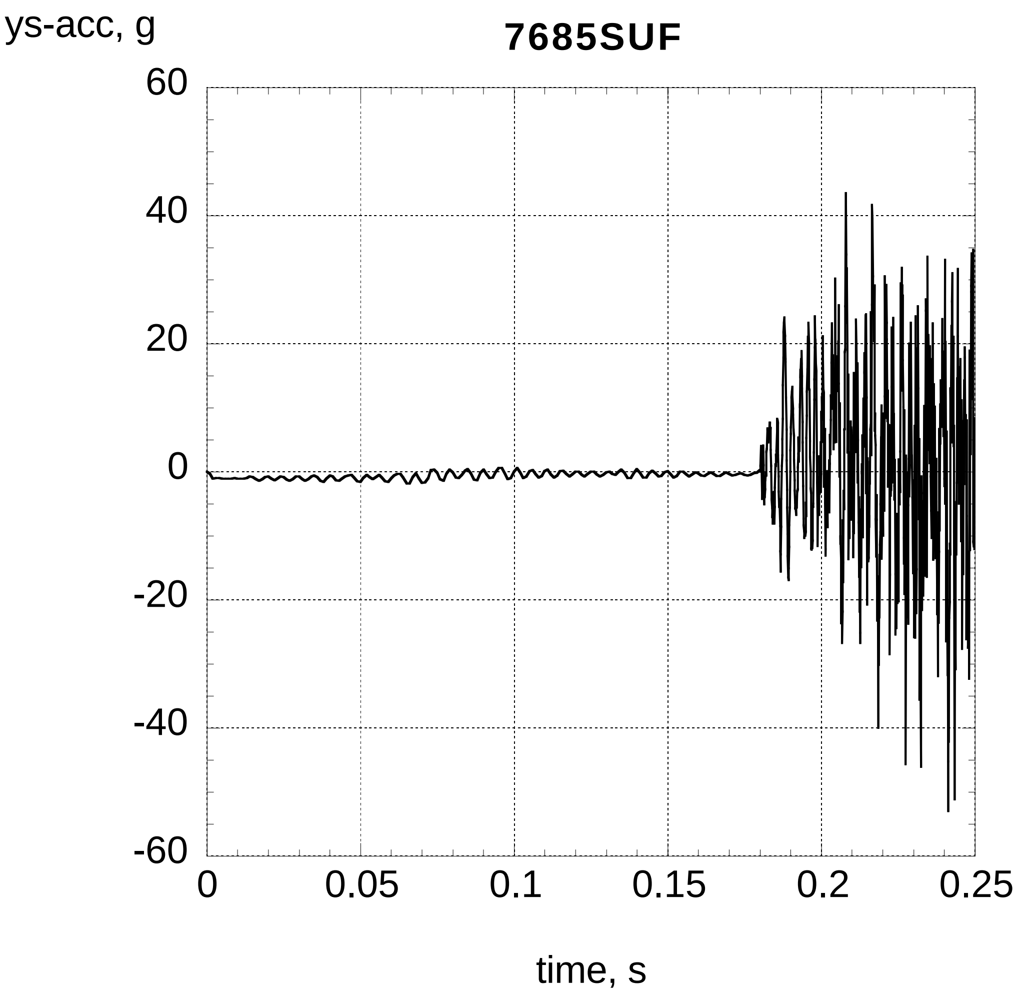

zs-acc, g
2452SUF
40
30
20
10
0
-10
-20
-30
-40
0
0.05
0.1
0.15
0.2
0.25
time, s


xs-acc, g
2468SUF
30
20
10
0
-10
-20
-30
0
0.05
0.1
0.15
0.2
0.25
time, s


ys-acc, g
2468SUF
30
20
10
0
-10
-20
-30
0
0.05
0.1
0.15
0.2
0.25
time, s


zs-acc, g
2468SUF
40
30
20
10
0
-10
-20
-30
-40
0
0.05
0.1
0.15
0.2
0.25
time, s


xs-acc, g
7685SUF
60
40
20
0
-20
-40
-60
0
0.05
0.1
0.15
0.2
0.25
time, s



ys-acc, g
7685SUF
60
40
20
0
-20
-40
-60
0
0.05
0.1
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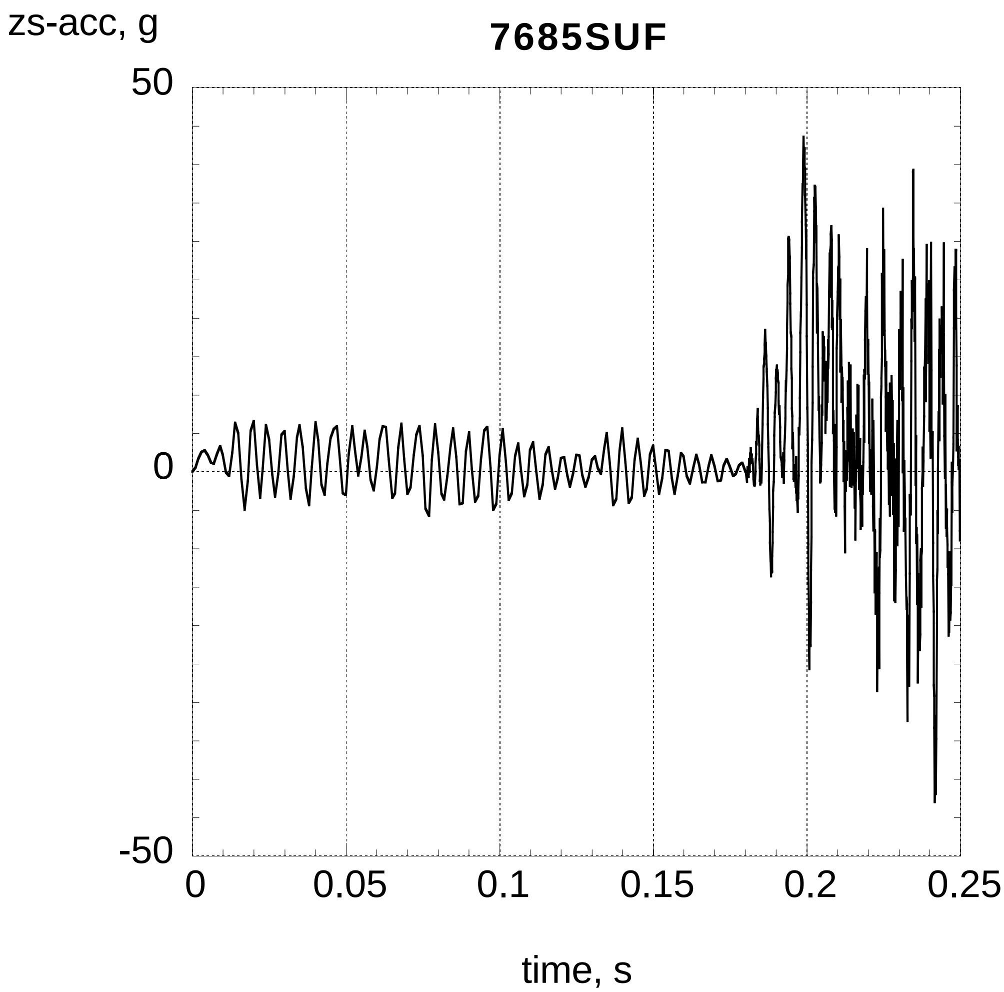
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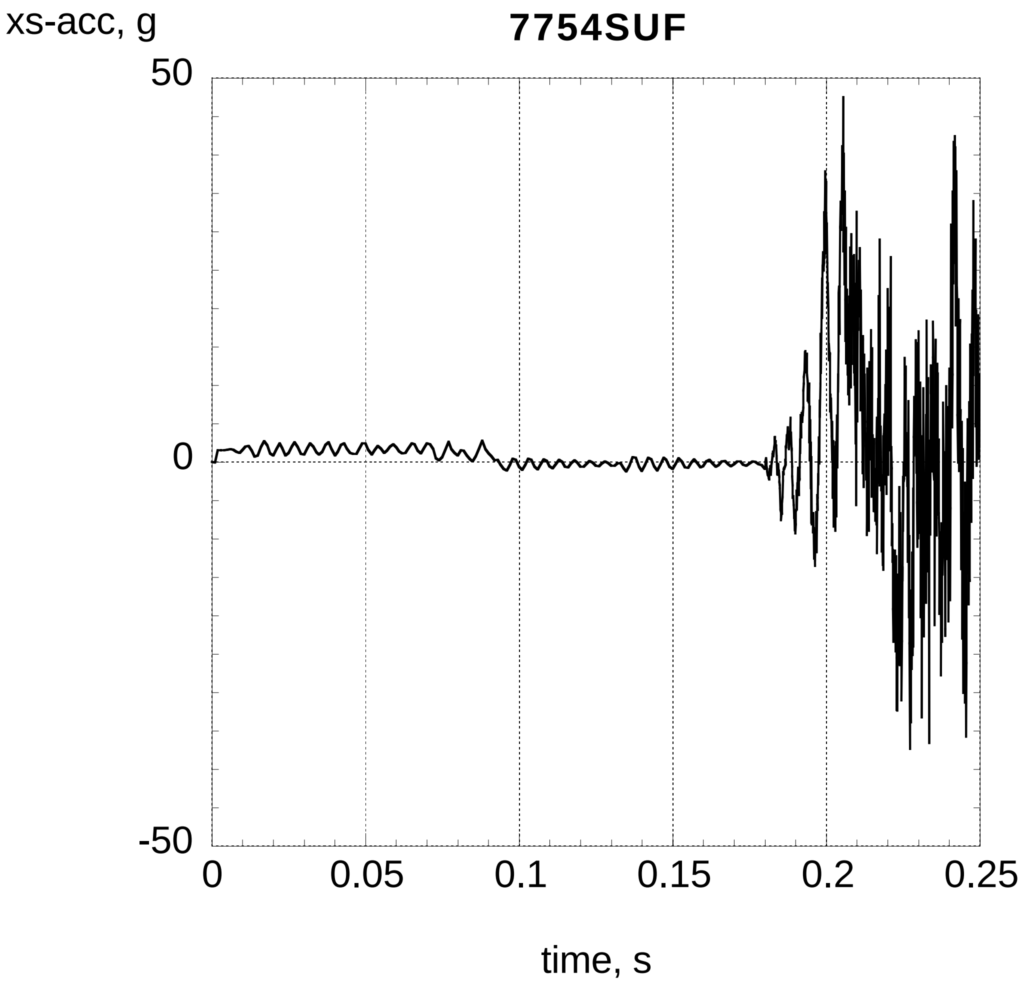
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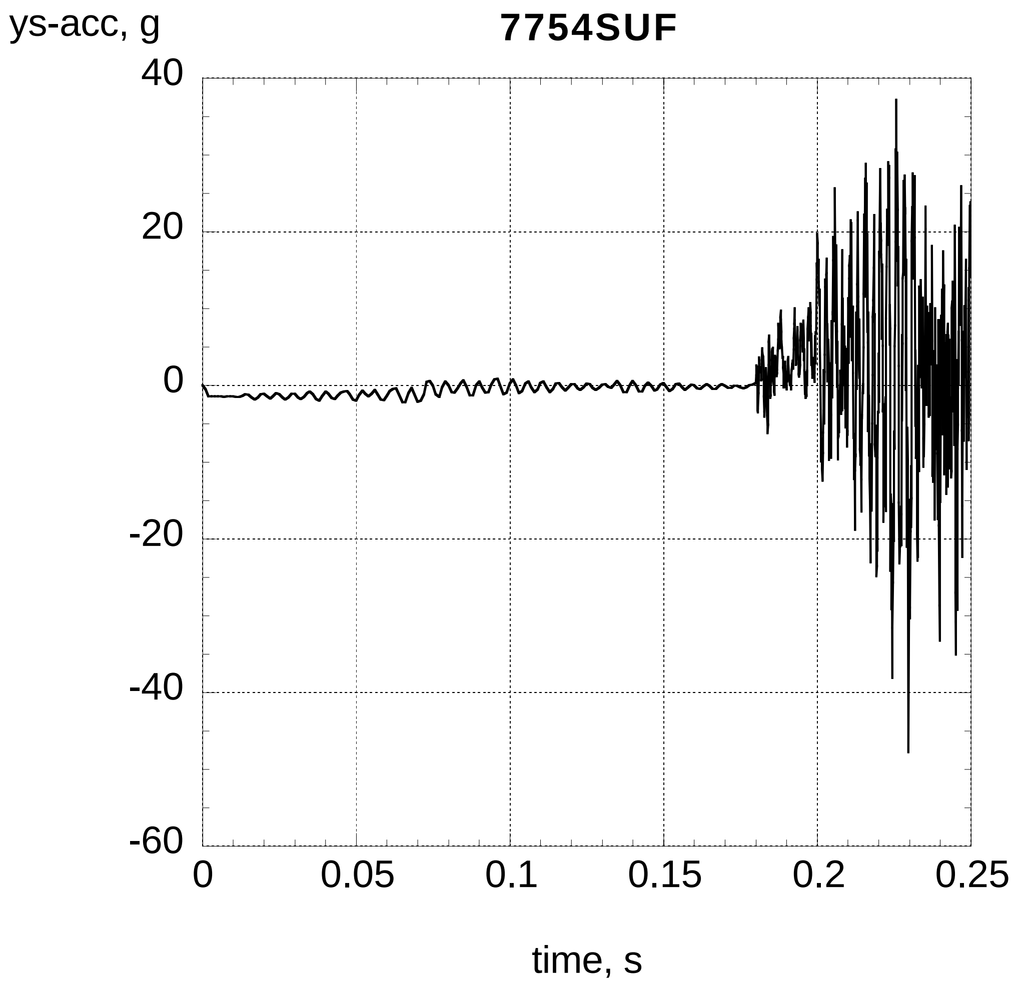
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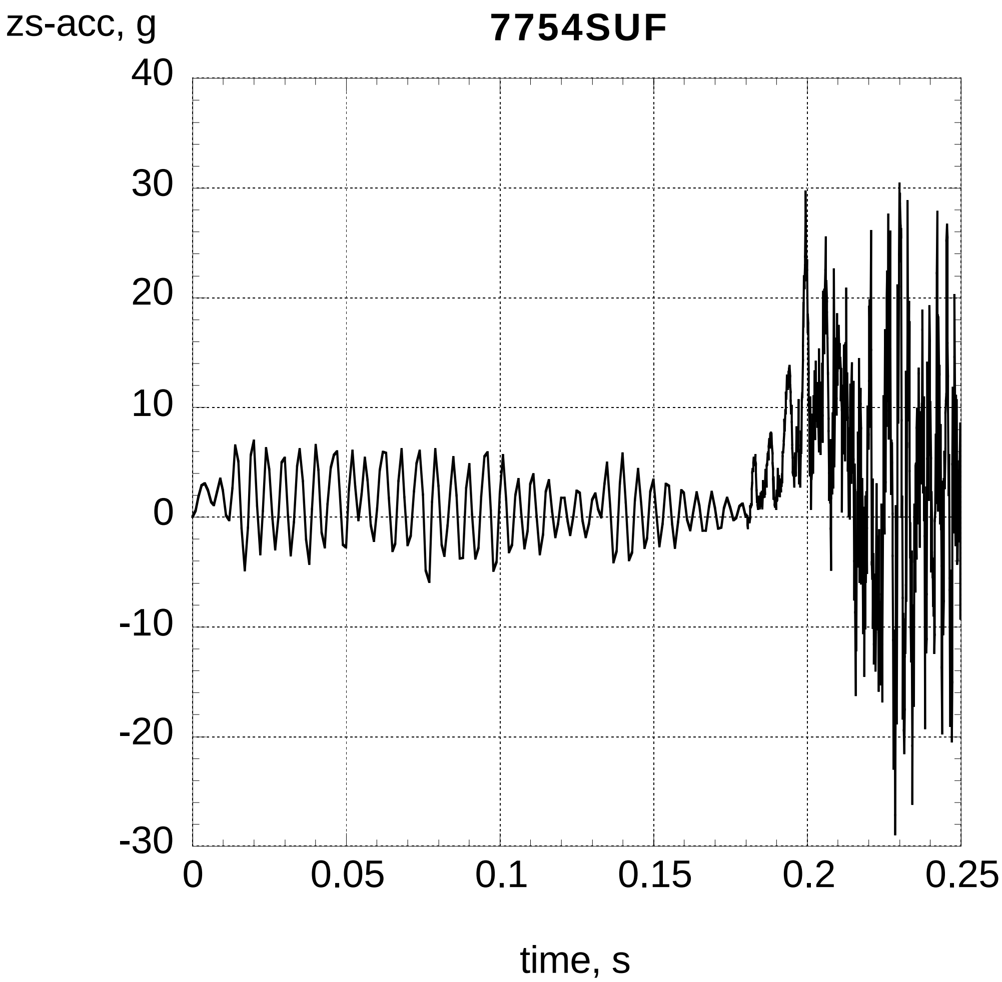
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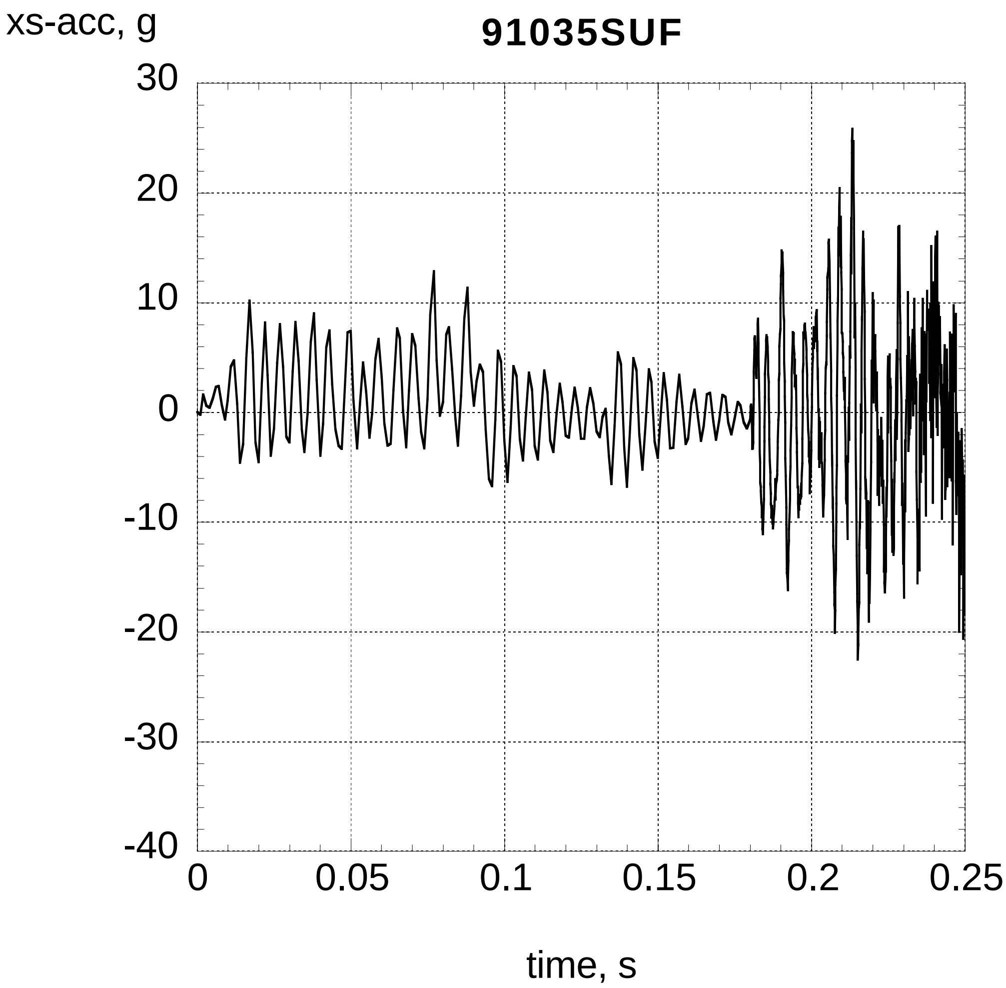

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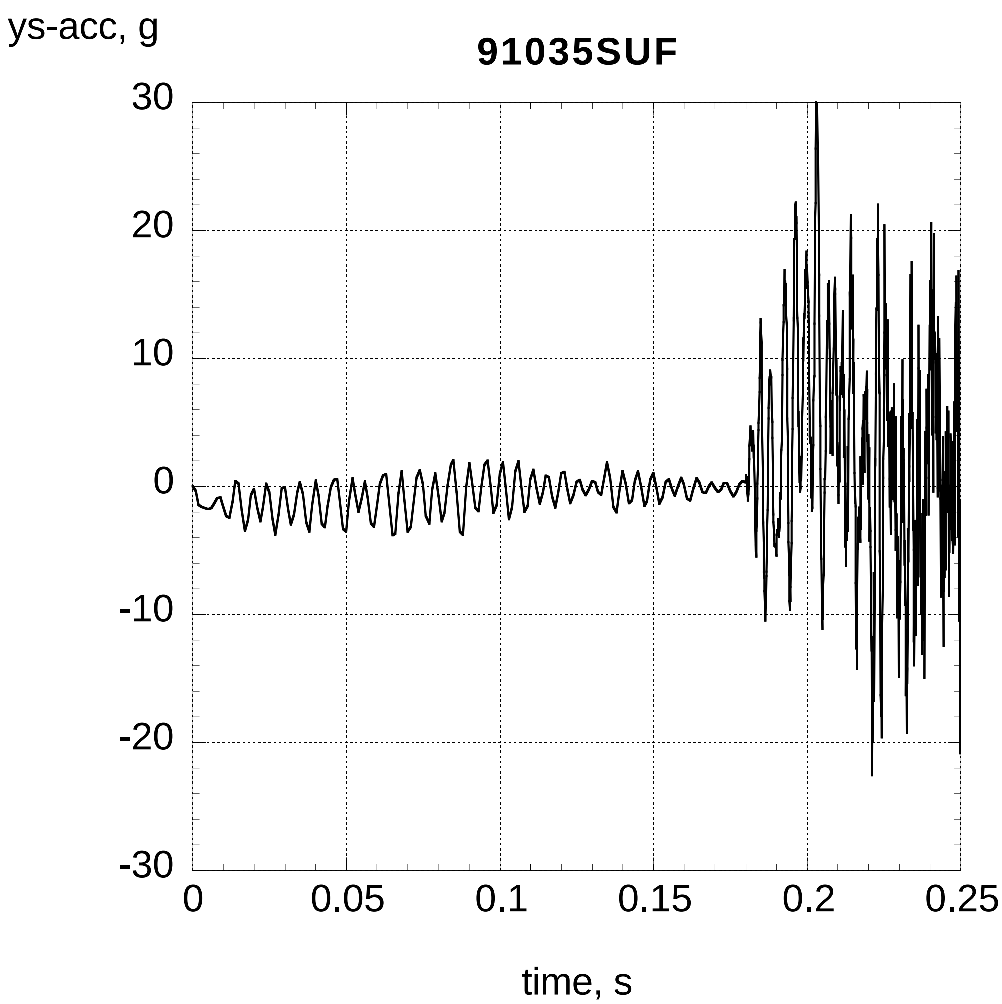
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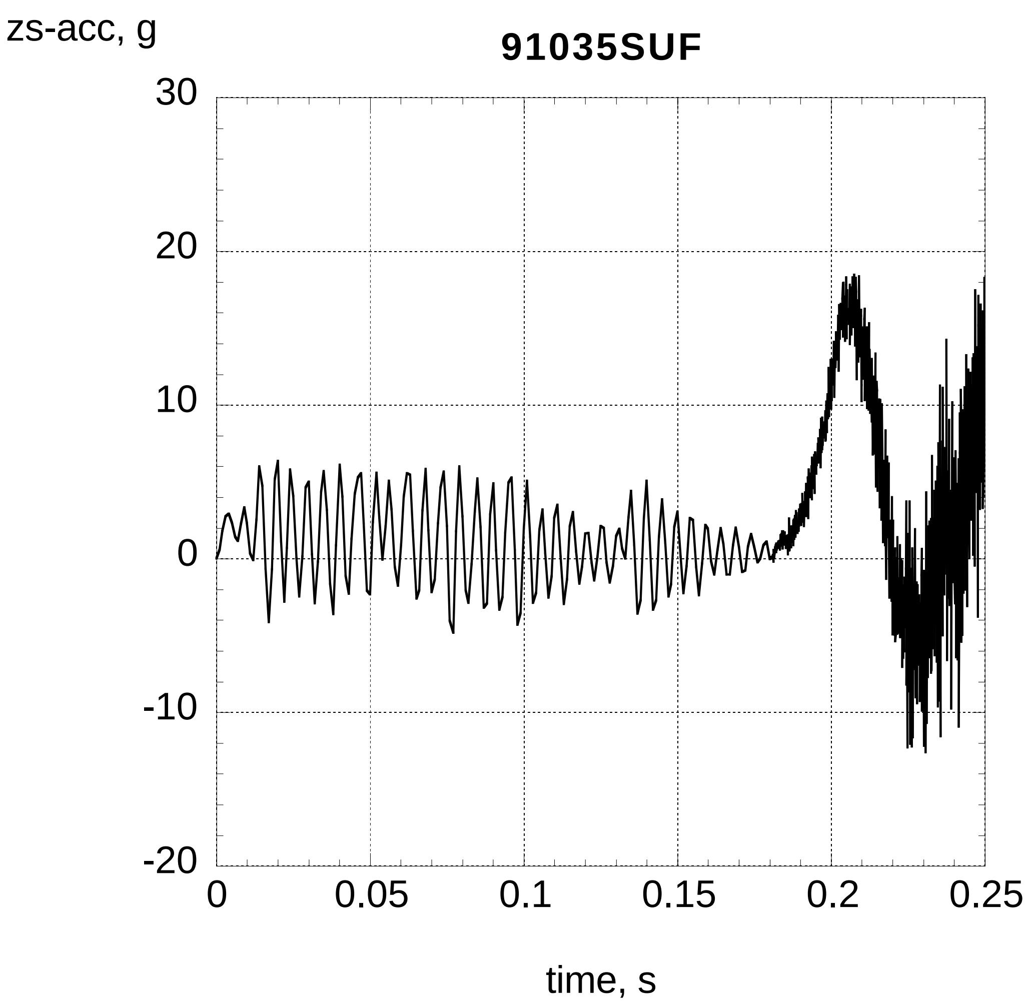

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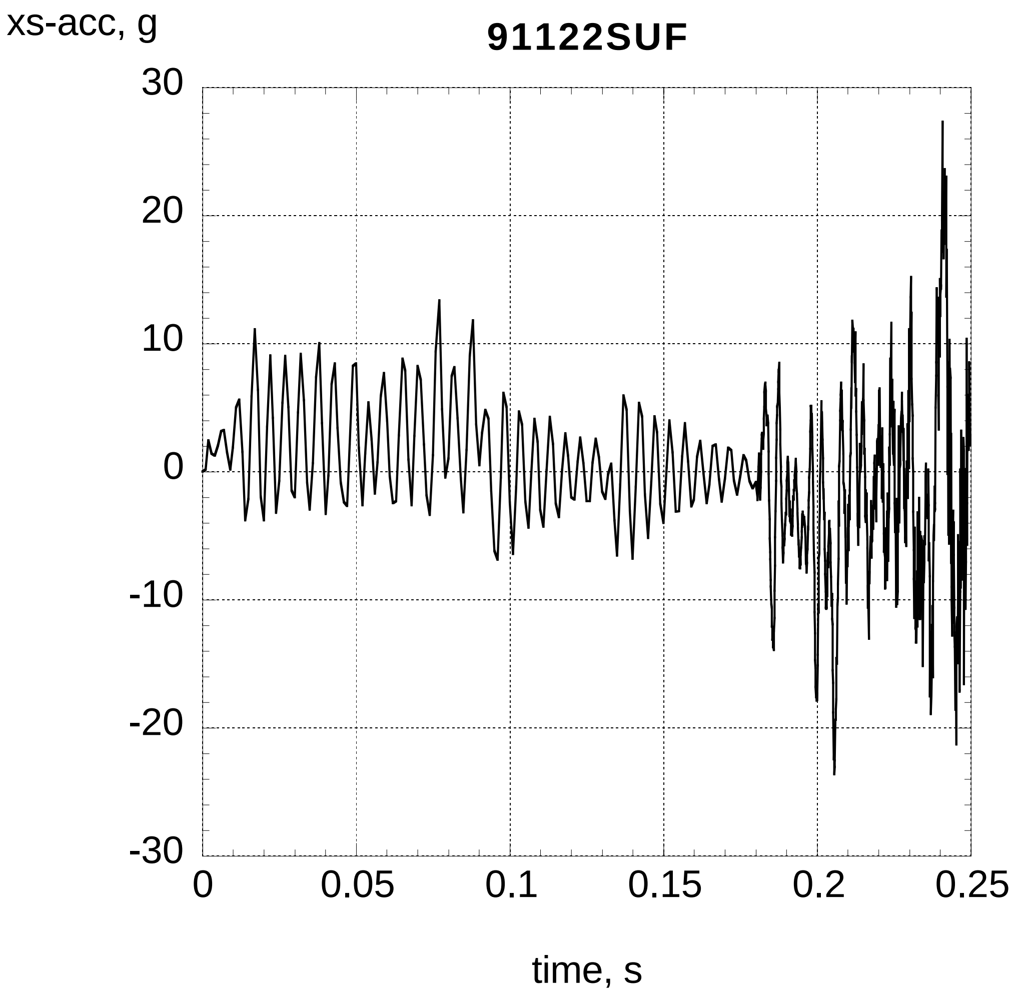
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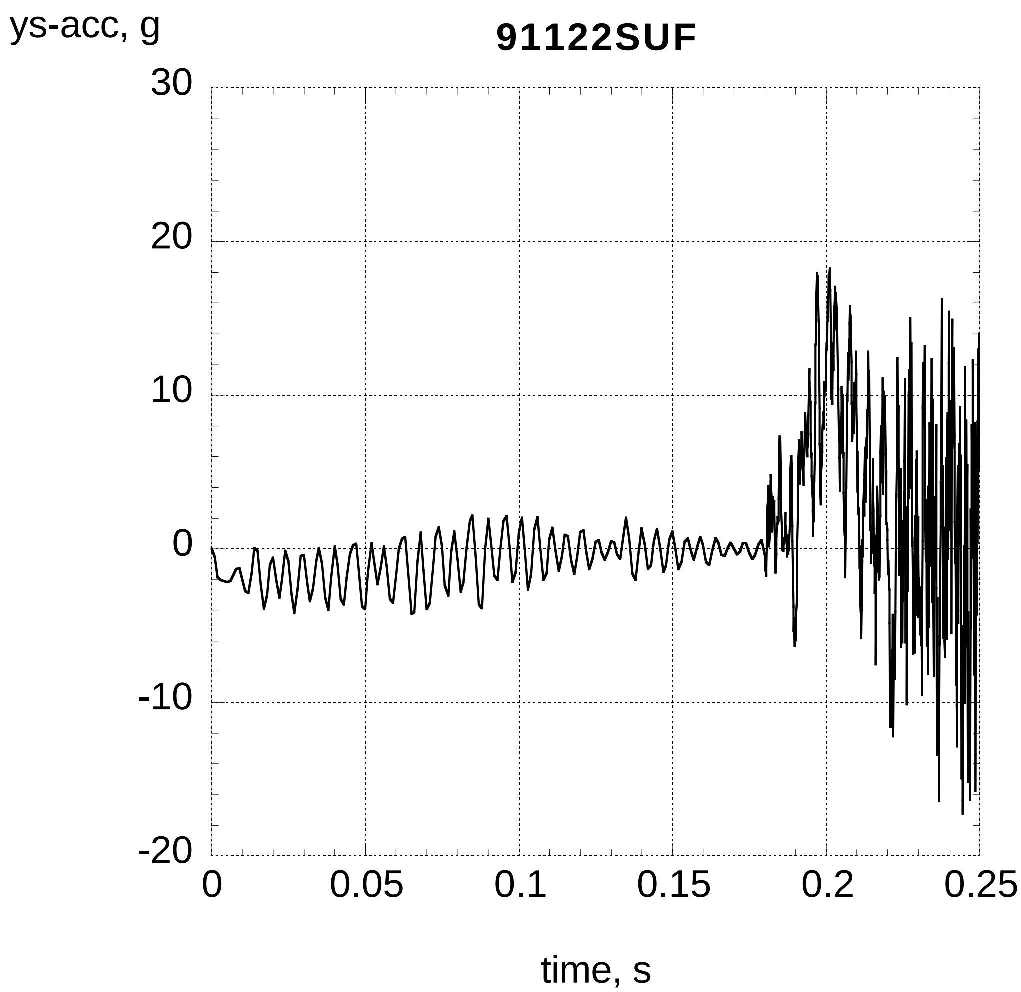
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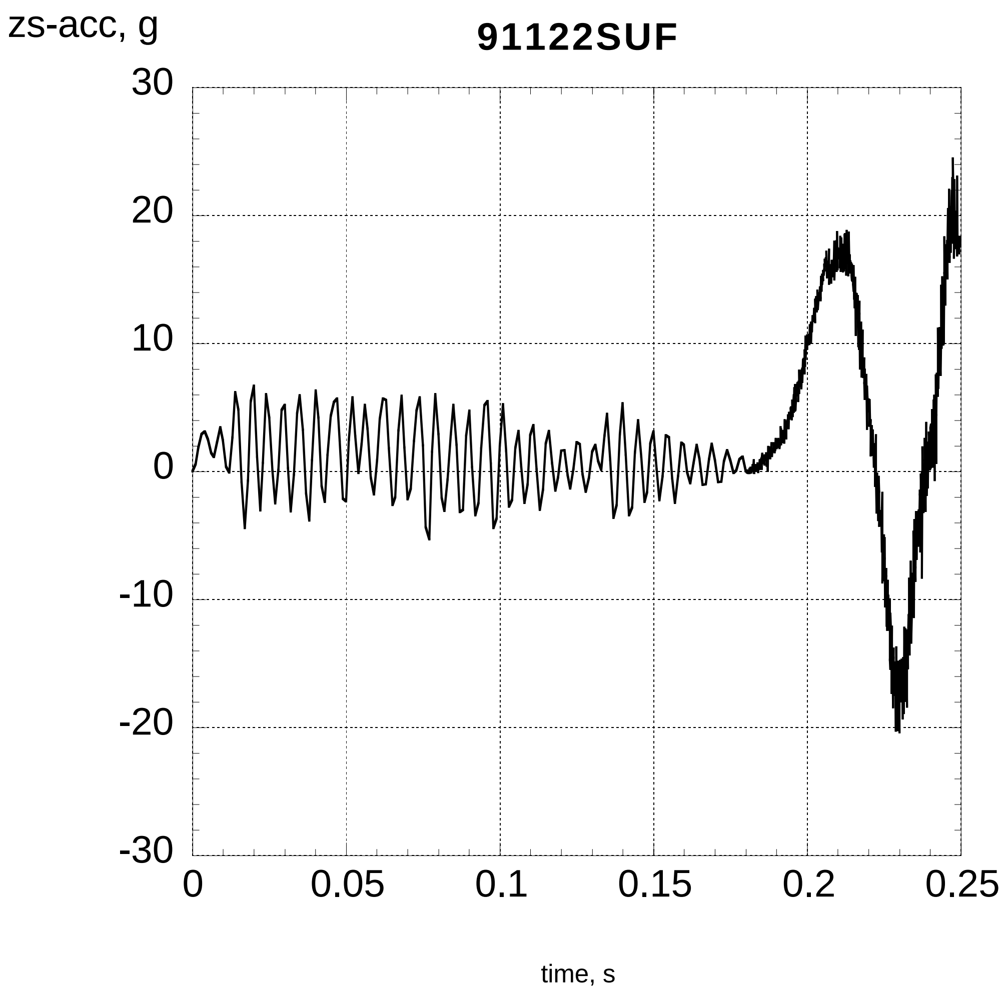
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13. ABSTRACT (Maximum 200 words)

Abnormal landing scenarios of the X-38 prototype Crew Rescue Vehicle (CRV) were modeled for three different cases involving non-deployment of landing gear with an explicit dynamic nonlinear finite element code, MSC/DYTRAN. The goal of this research was to develop models to predict the probability of crew injuries. The initial velocity conditions for the X-38 with chute deployed were 10 ft/s vertical and 57 ft/s longitudinal velocity. An MSC/NASTRAN structural model was supplied by JSC and was converted to a dynamic MSC/DYTRAN model. The MSC/NASTRAN model did not include seats or floor structure; thus, the acceleration of a lumped-mass attached to the bulkhead near each assumed occupant location was used to determine injury risk for each occupant. The worst case for injury was nondeployment of all gears. The mildest case was nondeployment of one main gear. Although a probability for minor injury was predicted for all cases, it is expected that the addition of energy-absorbing floor structure and seats would greatly diminish the probability of injury.

14. SUBJECT TERMS
X-38, Crew Rescue Vehicle, landing gear, DYTRAN, nonlinear finite element analysis, landing mishap, impact analysis

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