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SIMULATIONS OF ROLLOVER TESTS

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ARMSTRONG AEROSPACE MEDICAL RESEARCH LABORATORY

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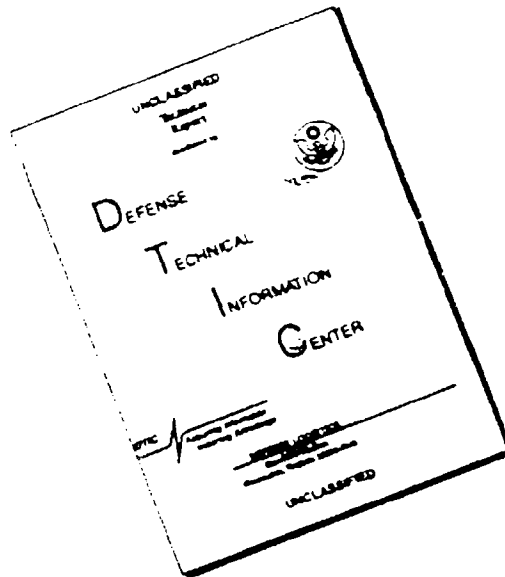
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Final Report

Simulations of Rollover Tests

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16. Abstract The motion of an occupant during a rollover crash is often violent and complicated. This motion needs to be studied so as to determine how best to protect an occupant during a rollover crash, and the best tool known is computer models which simulate the motion of an occupant. It was the Air Force's Articulated Total Body (ATB) model which was used. The accuracy of the simulations by this model has to be determined through a limited number of rollover crash tests. Five such tests were conducted under this program using a specially designed rollover test device, and the corresponding simulations of the motion of a dummy occupant are presented. The accuracy of the simulations obtained for these five tests with a rollover test device and the similar accuracy for one full-scale crash test conducted earlier on a different testing program provide confidence that an occupant's motion during a rollover crash, whether belted or unbelted, can be satisfactorily simulated by the Air Forces ATB.			
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INTRODUCTION

During vehicle crashes in which rollover occurs the motion of the vehicle can be quite complex and violent resulting in extensive motion and multiple impacts with vehicle interior by the occupant. If the occupant is unrestrained, the interior motion can be considerable and ejection from the vehicle is common [Ref. 1]. Very often rollover occurs after a serious frontal or side impact which may cause initial injury to an occupant. An occupant already injured may be very susceptible to additional injuries during the subsequent rollover phase of the crash. It has been observed that there is a high probability of head/neck complex impact during rollover and that partial ejection of the head occurs with approximately equal frequency whether the occupant is belt restrained or unrestrained [Ref 1]. Accident investigations have established that partial ejection, especially of the head, is associated with a high risk for serious or fatal injury.

The best ways to protect an occupant during a rollover crash need to be investigated. One viable means for pursuing such an investigation is through computer predictions of an occupant's motion during a rollover crash. Such predictions can establish how best, for example, to modify belt restraints or vehicle structure so that there is less probability of par-

tial or full body ejection or how best to use padding to mitigate injuries. Many other aspects of body and vehicle interaction can also be investigated.

The alternative to computer predictions is extensive full-scale rollover crash testing of vehicles with dummy occupants. Both the analytical simulation and testing approaches have their individual shortfalls, but, performed in conjunction with one another, these shortfalls are offset. The analytical simulation approach allows extensive parametric investigations with perfect repeatability, while the experimental testing provides for baseline responses that can be used for validation of or interpolation by modeling. Such tests are generally expensive, require long set-up times and are not suitable for situations involving a large number of variable conditions. The modeling allows certain specific questions to be readily answered; such as, how best to minimize the probability of partial head ejection, how best to use padding to decrease the potential for injury or to evaluate the effect of roof crush. One of the problems during testing is that the motion of a vehicle during a rollover crash cannot be accurately controlled. Without accurate control of vehicle motions the effect of variation in vehicle motion, restraint system design or other protective measures cannot be assessed. In contrast, the motion of a vehicle can be exactly specified during computer predictions of an occupant's motion allowing parameter studies to be easily conducted and the cost of each prediction is a very

small fraction of the cost of full-scale crash testing. It is essential, of course, to have confidence in the accuracy of the computer prediction of an occupant's motion, therefore parallel experimentation, or at least reasonable quantitative empirical data are necessary.

BACKGROUND

The need to predict an occupant's motion during crashes in general has long been recognized. The National Highway Traffic Safety Administration (NHTSA) recognized such a need and initiated and supported the development of the Calspan Crash Victim Simulator (CVS) [Ref. 2]. The Armstrong Aerospace Medical Research Laboratory (AAMRL) at Wright-Patterson Air Force Base has used the CVS to predict the human body's dynamic response to mechanical forces. Furthermore, AAMRL has modified the CVS in order that it can better address specific Air Force concerns [Ref. 3-4]. The modified version of the CVS is identified as the Articulated Total Body (ATB) model. The ATB, having been derived from the CVS, is fully capable of predicting the motion of an occupant during a rollover crash. However, to be effectively used for such studies the ATB model must be validated against baseline crash test data.

In order to obtain such data a well controlled, fully instrumented crash test was conducted at the Southwest Research

Institute (SWRI). In this test a passenger car with a belt restrained dummy was impacted into the end of a turned down guardrail at 60 mph. The ramping effect of the turned down guardrail induced vehicle rotation resulting in four full rollovers. Two high speed motion picture cameras, mounted inside the vehicle, recorded the dummy's motion [Ref. 5]. It was these data that were used in conjunction with the ATB model to establish the method of dynamically predicting the motion of an occupant during a complex rollover crash. The analytically predicted motion of the dummy agreed quite well with the dummy's motion as recorded on the test film.

Measurements of the vehicle's motion during the SWRI test were made from high speed motion pictures and used as input to the ATB model, as described in Reference 5. The vehicle interior and restraint system were defined to match the test, and an estimate of the interactions to occur was made. Several simulations were made to add interactions that were not originally considered. The final simulation predicted the motion of the dummy recorded by high speed motion picture cameras during the 4.5 seconds of the entire crash.

In order to refine and further validate this methodology, results from six controlled rollover tests, conducted by Transportation Research Center of Ohio [Ref. 6-11], were compared to results from simulations of the same events. These tests were conducted using a rollover test device to initiate rollover and with a dummy placed in either the driver's or

front passenger's seat. After each of the tests were conducted, the vehicle motion was reconstructed from films of the test for input into the ATB model. Other data from the test were also analyzed for use by the model and then simulations were made of the occupant motion. The results of the simulations were then compared with data collected during the testing.

DESCRIPTION OF ROLLOVER TESTS

The six rollover crash tests were conducted using a rollover test device (RTD) developed by the MGA Research Corporation for NHTSA [Ref. 12]. The car was mounted on the RTD as shown in Figure 1, with an initial roll angle. The RTD wheels could be rotated, allowing the RTD and the test vehicle to be crabbed at an initial yaw angle (Figure 2). Two pneumatic cylinders were used to apply a rotational velocity to the platform on which the car was mounted. The test procedure was to tow the RTD by cable along the guiderail to obtain an initial linear velocity. Upon reaching this velocity the car was released from the platform, the cylinders were actuated producing angular rotation of the platform and the RTD was decelerated. The general test layout for the six tests is shown in Figure 2. Break-away reference poles were placed throughout the test area for use in reconstructing the vehicle motion and 500 frame-per-second cameras filmed the test events from several angles. After release, each of the cars

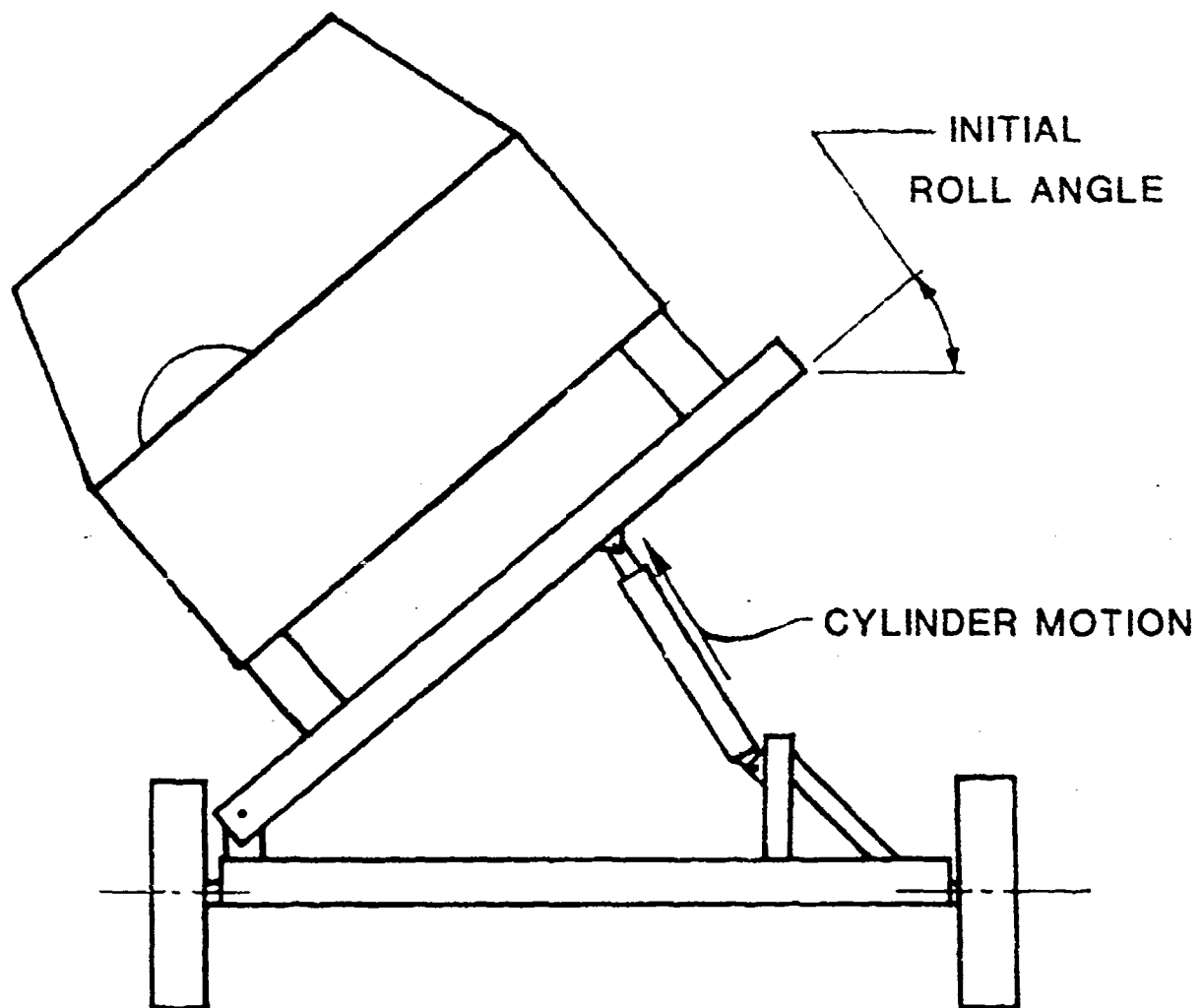


Figure 1 - Test Vehicle Mounted on the Rollover Test Device (RTD)

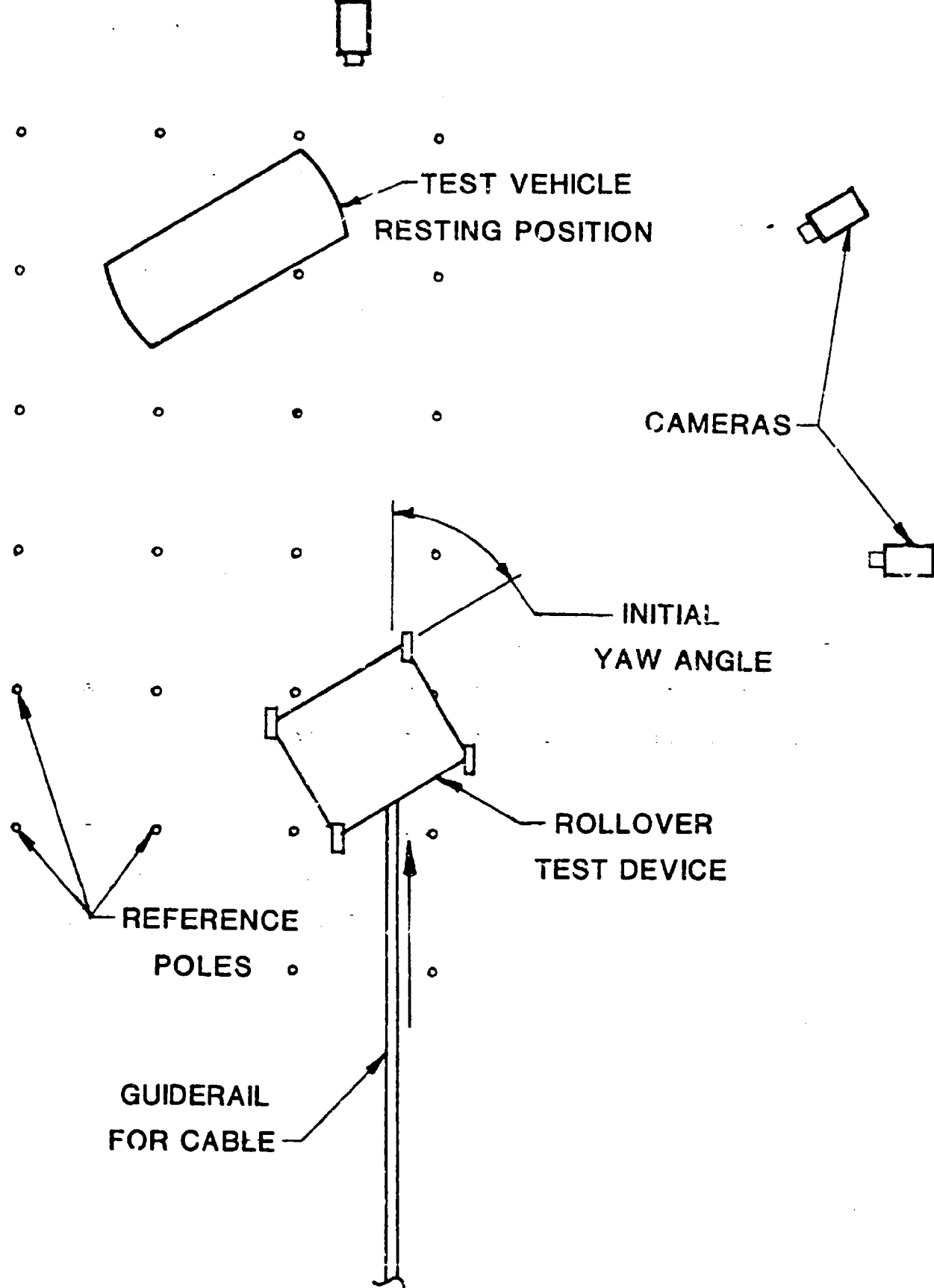


Figure 2 - Test Layout

landed on their left side and rolled onto the roof. Some slid to a stop in this position while others continued to roll. Accelerometers and angular rate gyros were mounted on the cars to provide additional information about the vehicle's motion.

Hybrid III and Part 572 dummies were used in the tests. These dummies have been developed for frontal impact testing and have not been assessed as being specifically suitable for rollover testing. However, these dummies were selected since they represent the state-of-the-art, possess adequate instrumentation capability, have established use experience in automotive testing and since no current dummy exists that is specifically designed for rollover testing.

In the test set-up, the dummy was positioned in the front seat of each car and, during the first two tests, was restrained by a three-point harness. The dummies were instrumented with head and chest accelerometers and the Hybrid III dummies, additionally with neck and femur load cells. Two high-speed cameras were mounted within the vehicles to film the dummy's motion during the test.

The six tests and their conditions are listed in Table 1. Film data from each of the six tests were analyzed to determine the vehicle's motion and then the occupant's motion was simulated using the ATB model. Since this was the first rollover test study utilizing the RTD, the first test, with

TABLE 1
TEST CONDITIONS

TEST NO.	CAR	INITIAL ORIENTATION	RELEASE VELOCITY	DUMMY	SEAT	RESTRAINT SYSTEM	NUMBER OF ROLLS	FINAL RESTING POSITION
1	1975 2-door Pinto	45 deg yaw 41 deg roll	17 mph	Part 572	Driver	3-Point Belt	1	Wheels
2	1981 4-door Reliant	42 deg yaw 41 deg roll	21 mph	Part 572	Driver	3-Point Belt	1-1/2	Roof
3	1984 4-door Accord	44 deg yaw 36 deg roll	21 mph	Part 572	Driver	None	1/2	Roof
4	1982 4-door Celebrity	45 deg yaw 39 deg roll	23 mph	Hybrid III	Driver	None	1	Wheels
5	1979 5-door Omni	45 deg yaw 39 deg roll	23 mph	Hybrid III	Front Passenger	None	1/2	Roof
6	1982 4-door Zephyr	60 deg yaw 35 deg roll	23 mph	Hybrid III	Front Passenger	None	1/2	Roof

the 1975 Ford Pinto, was used to identify procedural problems. The motion of the Pinto in the first test could not be accurately reconstructed or verified because not enough landmarks had been placed in the test area. This was corrected in subsequent tests, but the results of this first test could not be used for computer predictions of the dummy occupant's motion. With this correction and some procedural changes, data from the remaining five tests were successfully used for occupant simulation. Extensive data were collected during each test and the simulation results were equally voluminous. Since all five tests and their simulations were identically conducted, only one test and corresponding simulation is discussed in detail and the results from the other four tests are presented in the Appendix. The fourth test, using a 1982 Chevrolet Celebrity, was chosen for the discussion [Ref. 9]. This test presented the greatest challenge for simulation because it had an unrestrained occupant, the vehicle rolled more than in most of the other tests, and it had the longest duration. This test's occupant motion simulation also yielded the best results.

VEHICLE MOTION RECONSTRUCTION

To simulate occupant motion, a prescription of the vehicle's linear and angular motion is required. Because of difficulties inherent in reconstructing six degree-of-freedom motion from accelerometer and angular rate gyro data, as described

in Reference 5, the films of the vehicle motion were chosen as the best source for obtaining the complete vehicle motion. The technique for obtaining the vehicle displacements from the vehicle motion films was developed in the guard rail rollover study [Ref. 5]. It was refined in this effort by reducing the number of vehicle landmarks to be digitized from six to one and by collecting the angular orientations directly, rather than calculating them from the digitized points. These refinements made the process easier and increased its accuracy.

The first step in the reconstruction process was to analyze selected film frames from two different camera views. In each view, the vehicle width was measured and one point on the vehicle and one point on a reference pole near the vehicle were digitized. Parallax error was corrected by using the measured vehicle width to scale the linear positions obtained from the digitization. These linear positions were then used to draw a computer image of the vehicle on a color graphics screen as viewed by one of the test cameras. The film image from that camera was then projected directly onto the graphics screen and the computer image rotated until it aligned with the film image. The vehicle orientations were saved for each film frame. The vehicle width data were then modified to account for the vehicle orientation when the width was measured, and the linear position data was rescaled using the new vehicle widths. The last step in this process was to condition both the linear and angular position data to

eliminate data collection and round off errors by smoothing the data with a user-controlled-parameter cubic spline smoothing routine.

Figure 3 shows the film images of the Celebrity at 600 msec intervals and the corresponding computer-generated images of the reconstructed vehicle motion. Time zero for the tests was defined by the front wheel of the RTD tripping a switch. This occurred before the vehicle was released or the cylinders actuated. The Celebrity was released from the rollover device after 600 msec and impacted the ground on its left, front side around 1500 msec. It then rolled onto its roof, slid for some time and finally rolled onto its wheels. There is no visible difference between the film and reconstructed motion.

Accelerometer and angular rate gyro data for the vehicle were collected and are compared to the calculated values obtained from the film analysis. The accelerometer data were not expected to match well due to the fact that acceleration is the second derivative of displacement, which was the measured quantity used to reconstruct the vehicle motion. Therefore, any small differences from the reconstruction process are magnified twice when comparing accelerations. The rate gyro data is considerably smoother than the accelerometer data and compares much better to the calculated rotation rates from the reconstructed motion. Figure 4 contains plots of these

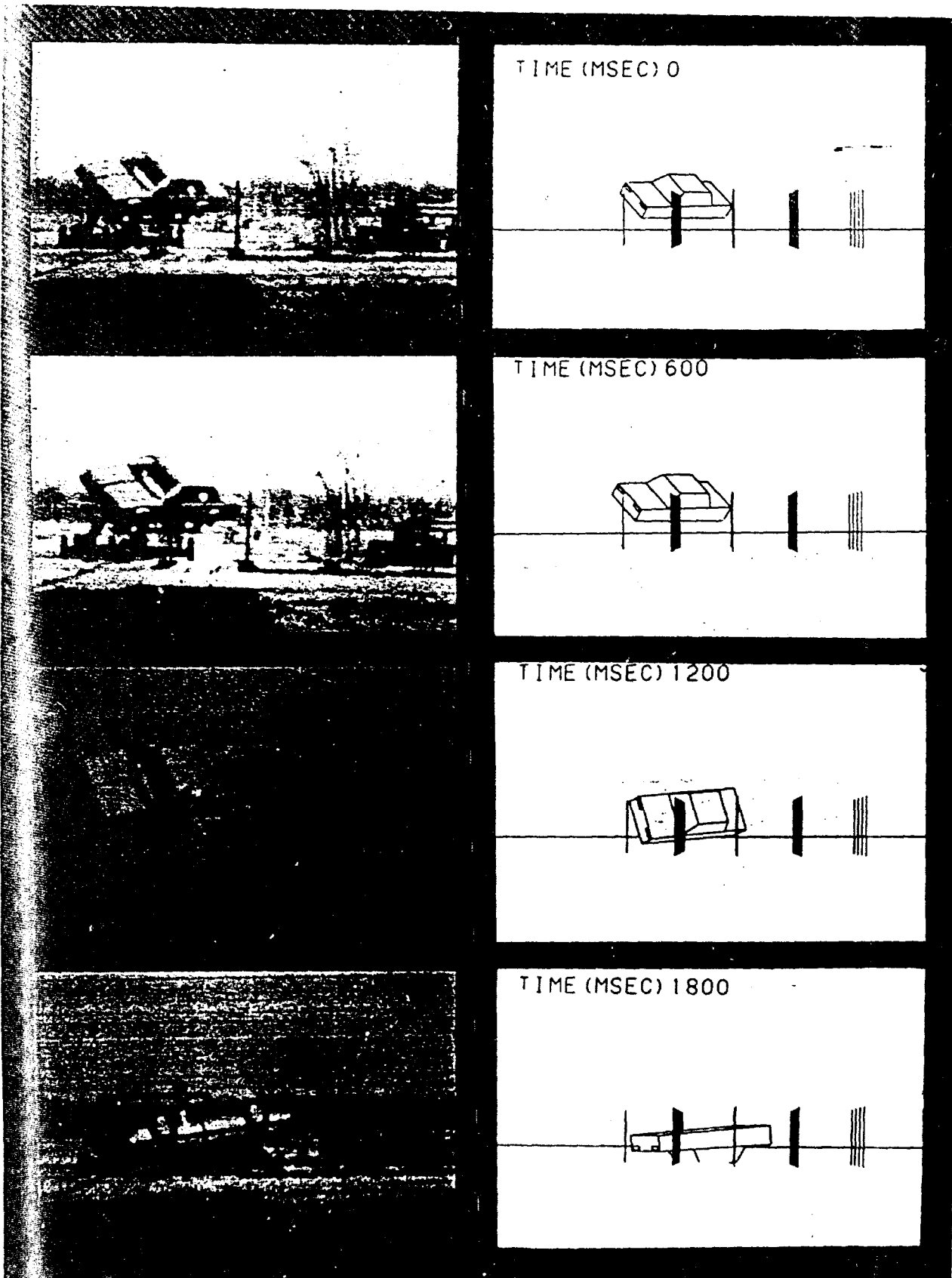


Figure 3 - Test No. 4, Celebrity
Test Film and Reconstructed Vehicle Motion

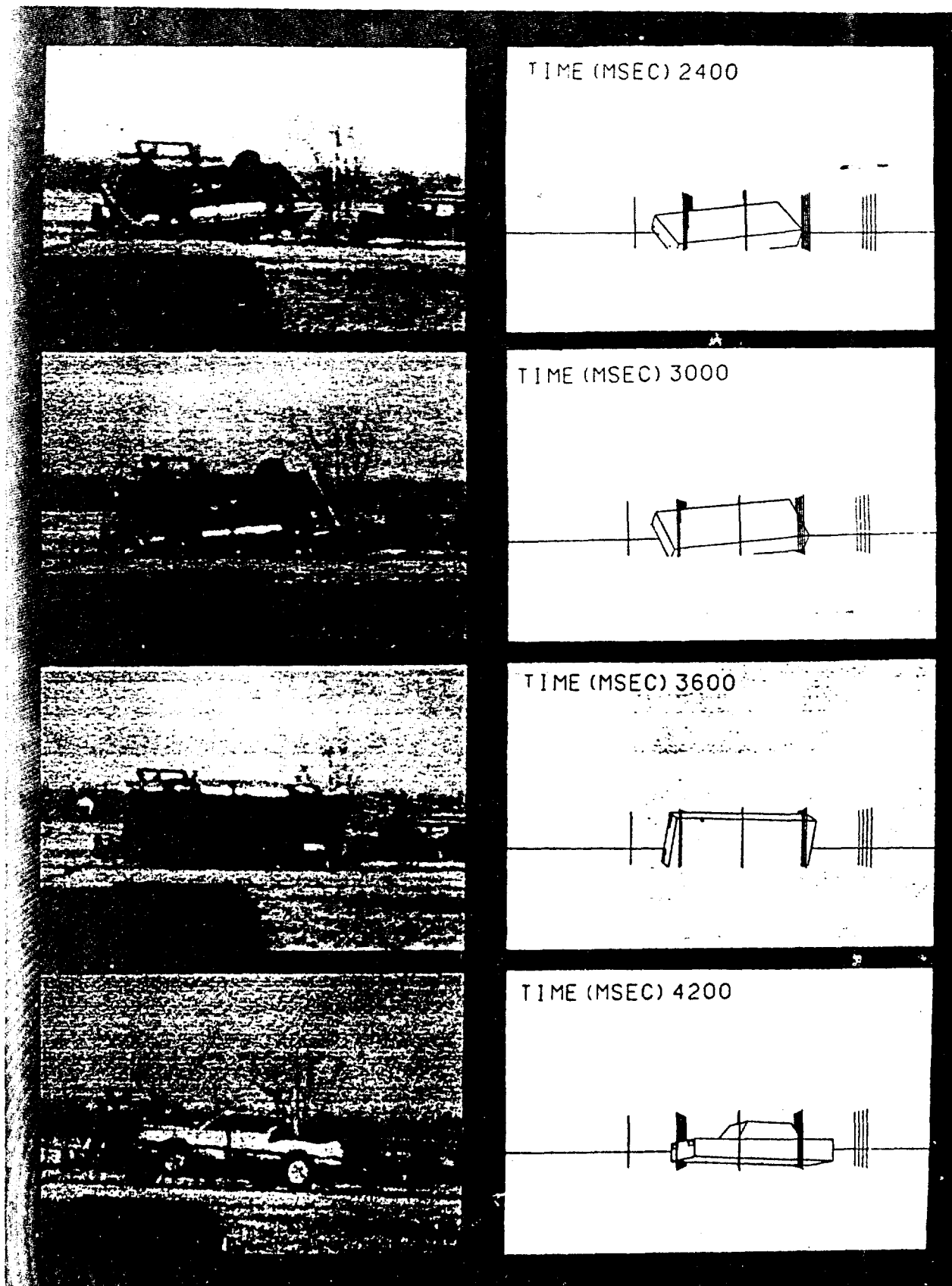
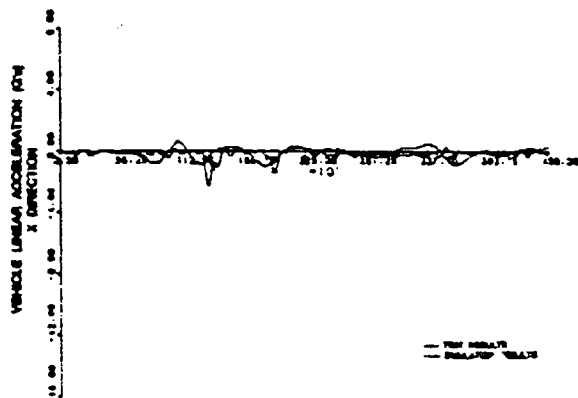
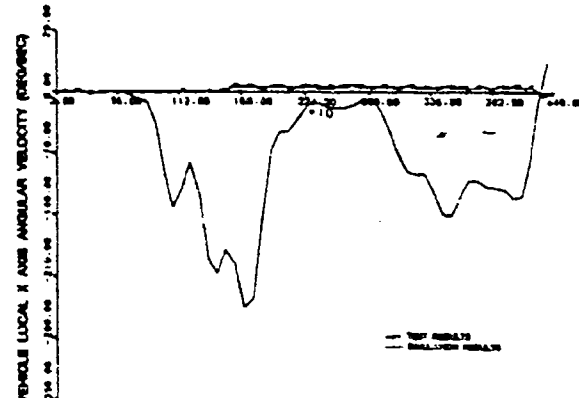


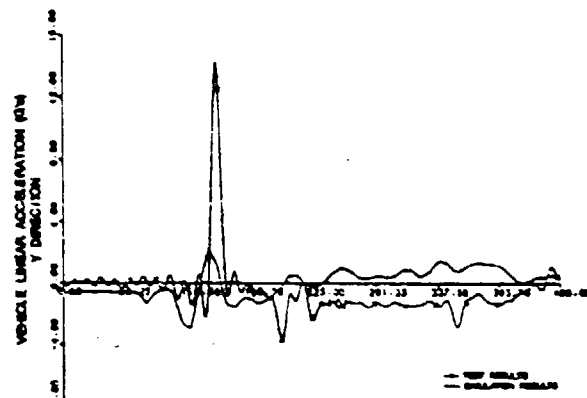
Figure 3 - continued



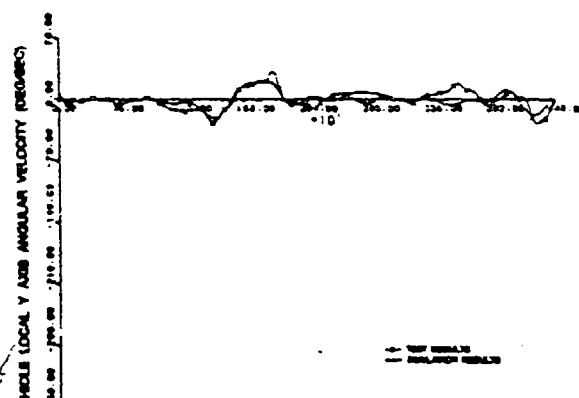
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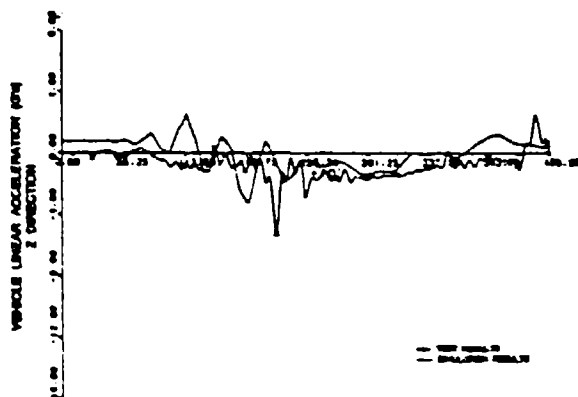
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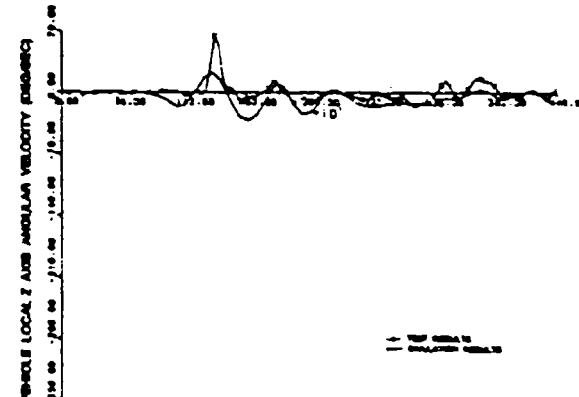
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TIME (MSEC)



TIME (MSEC)



TIME (MSEC)

Figure 4 - Test No. 4, Celebrity
Vehicle Tri-axial Accelerometer and Angular Rate Gyro Data
From Test and Reconstructed Motion

comparisons from the Celebrity test, with the linear accelerations on the left and the angular velocities on the right. As expected, the accelerations do not always agree, but the magnitudes and trends are generally similar. The large acceleration spikes in the experimental data were filtered from the reconstructed motion by the process of collecting displacements, and the offset difference in the Y and Z accelerations is due to the initial calibration zeroing of the accelerometers in the test. Accelerometer measurements, as well as the ATB model calculations, include gravitational effects. However, in setting up the vehicle tests, the accelerometers were reset to zero after the vehicle was put in its initial roll position, resulting in an offset of a resultant 1G in the Y and Z directions. Since the ATB model correctly calculates the acceleration values, this offset is reflected in the plots. The X axis rate gyro failed in this test, as shown in the plot, but the angular velocities in the other two directions compare very favorably.

OCCUPANT SIMULATIONS

SET-UP

Besides the three-dimensional motion of the vehicle, setting up an occupant dynamics simulation requires a description of the dummy's characteristics, the layout of the vehicle interior, the force-deflection characteristics for each possible contact of dummy segments and vehicle surfaces and the seat belt description. A number of simulations of each test were necessary to completely define these characteristics. After all the specifications were finalized for a particular test, the final simulation was made.

Dummy Design

The first three crash tests were performed using an Alderson Part 572 dummy, while the remaining three tests utilized a Hybrid III dummy. The data set describing the segment properties and joint characteristics of the Part 572 dummy was obtained from the Validation of the Crash Victim Simulator Report, Volume 2 [Ref. 2]. However, the unavailability of a corresponding data set for the Hybrid III dummy dictated that the Part 572 data be used in all six simulations.

The ATB dummy model consists of 15 segments connected by 14 joints. The segment geometric and inertial properties, and joint characteristics of the model are the same as those of a Part 572 dummy. The segments are geometrically overlapped

and connected to each other at pivot points, or joints, that remain fixed relative to their associated segments and exhibit ranges of motion and resistive characteristics appropriate for the articulations they represent. Consequently, the knees are modeled as pin joints; the torso and neck, which can bend in any direction, are modeled as universal joints; and the hips, shoulders, elbows, and ankles are modeled as Euler joints, in which some axes are free to rotate and others are locked.

Vehicle Interior

For each of the six tests, a specific vehicle interior was defined. For the Celebrity simulation, as for all the others, the interior was measured and the data used to define the contact planes representing each possible interacting surface. The steering wheel geometry was modeled by an ellipsoid with the appropriate size and shape. This same process was used for all of the simulations.

The potential interactions between body segments and vehicle surfaces were identified from the films of the occupant motion, and for each interaction a force-deflection function was defined. These functions define the normal and tangential contact forces applied to the segment as a function of the amount of mutual deflection or, geometrically, the intersection of the segment and plane. The particular functions used were those which gave good results in the SWRI rollover

study [Ref. 5] and in a study of child motion during panic braking [Ref. 13]. The contact planes and the force-deflection characteristics were kept constant and not adjusted to provide a better fit to the observed data.

The 3-point harness restraining the dummy in the first two tests was modeled using the techniques described in Reference 5. The lap and shoulder belts were modeled independently, with both belts' endpoints rigidly anchored to the vehicle. The shoulder belt was attached to the upper, middle, and lower torso segments, and the lap belt to the lower torso and upper legs of the dummy model. Since the actual seatbelts were fed out of a reel instead of being rigidly attached to the vehicle, the stress-strain functions in the simulations were adjusted to compensate for this difference.

Initial Balancing

A unique problem associated with seating the occupant in each of the tests was encountered. Initially, the cars were placed upon the rollover device at approximately a 40 degree angle. However, it was necessary for the dummy to stay in the standard seated position until the vehicle started its rolling motion. The dummy was kept from falling over in the actual tests by tying a string around the neck, bringing it through the passenger side window, and tying it to the outside door handle. The assumption was that when significant motion of the car began, the string would break and the dummy

would be free to move in its natural fashion. Achieving the same objective in the simulations was more difficult. Several methods were attempted: inserting, between the upper torso and the vehicle, an initially locked sliding joint that would unlock at a specified force level; applying a time-dependent force to the neck and releasing it at the time the string broke; connecting the neck to the door with a harness belt; and adding small contact surfaces that hold the dummy in place until the dummy moves sufficiently to slip by them. The last method, using the small contact planes, was chosen for most of the simulations. However, problems in the Omnitest prompted a different approach for its simulation. Careful examination of the film revealed that the string holding the dummy in place actually never broke, so that its presence significantly affected the dummy's motion. Therefore, it was necessary to simulate the string throughout the simulation, even though this was not intended and did not represent a real-world condition. The method used to represent the string was a harness system consisting of one belt connecting the neck to the vehicle door. Although this did not precisely duplicate the string's effect, it sufficed. The harness belt did introduce an unexplained ringing effect that is evident in the acceleration plots in the Appendix.

Vehicle Deformation

One aspect of the rollover motion is the possibility of vehicle deformation that results in structural intrusion into

the passenger compartment. The most common incidence of this is roof crush. In a number of cases, as the car rolled onto its roof, the force of the contact with the ground caused the roof to cave in and severely changed the shape of the interior structure. This intrusion often influenced the occupant motion and it would have been desirable to duplicate this situation in the simulations. Although it is possible to simulate this effect with the ATB model, it was not performed in this study. Because roof crush was not anticipated prior to testing, appropriate measurements to accurately describe the motion of the roof were not made. The test films could be analyzed to reconstruct an estimate of roof motion, but this method would require significant additional effort to collect the data and manipulate it for input to the ATB model. Therefore, the simulations were run only until the time that roof crush affected the occupant motion.

OCCUPANT RESULTS

VIEW Graphics

For each of the six tests, the dummy motion was recorded by two motion picture cameras mounted inside the car. The rear camera, located in the back seat, viewed mainly the head, shoulder, and arm motion. The front camera was mounted on the front edge of the front seat on the side opposite the dummy. It was positioned to view the majority of the dummy motion. In general, the front camera view was the preferred

one since it showed more of the dummy's motion. However, in some cases, during the course of the rollover motion, the dummy moved so as to obscure the front camera lens' view. For these tests, the rear view was used. The locations of the chosen cameras were used as input in the VIEW graphics program to produce the corresponding pictures of the simulated motion for comparison to the filmed motion.

In the Celebrity test, the vehicle was traveling at an initial speed of 23 mph and was yawed at 45 degrees. The dummy was initially seated in the driver's seat and was unrestrained. Figure 5 shows the rear camera view comparison of the simulated and experimental results in 300 msec intervals. For the first 900 msec, there is no noticeable movement as the car is being carried down the track. By 1200 msec, the vehicle is released from the rollover device and is falling off the cart, and the dummy is rising out of the seat and moving toward the driver's side door. The most violent motion occurs at approximately 1500 msec when the car impacts the ground. The dummy is thrown against the roof and the driver's side door and, as the vehicle continues its rolling motion, the dummy bounces back into the seat and then over into the passenger side of the car. Finally, as the vehicle stops rolling and settles back on its wheels, the dummy falls over onto the bench seat with only its right shoulder visible from the rear view.

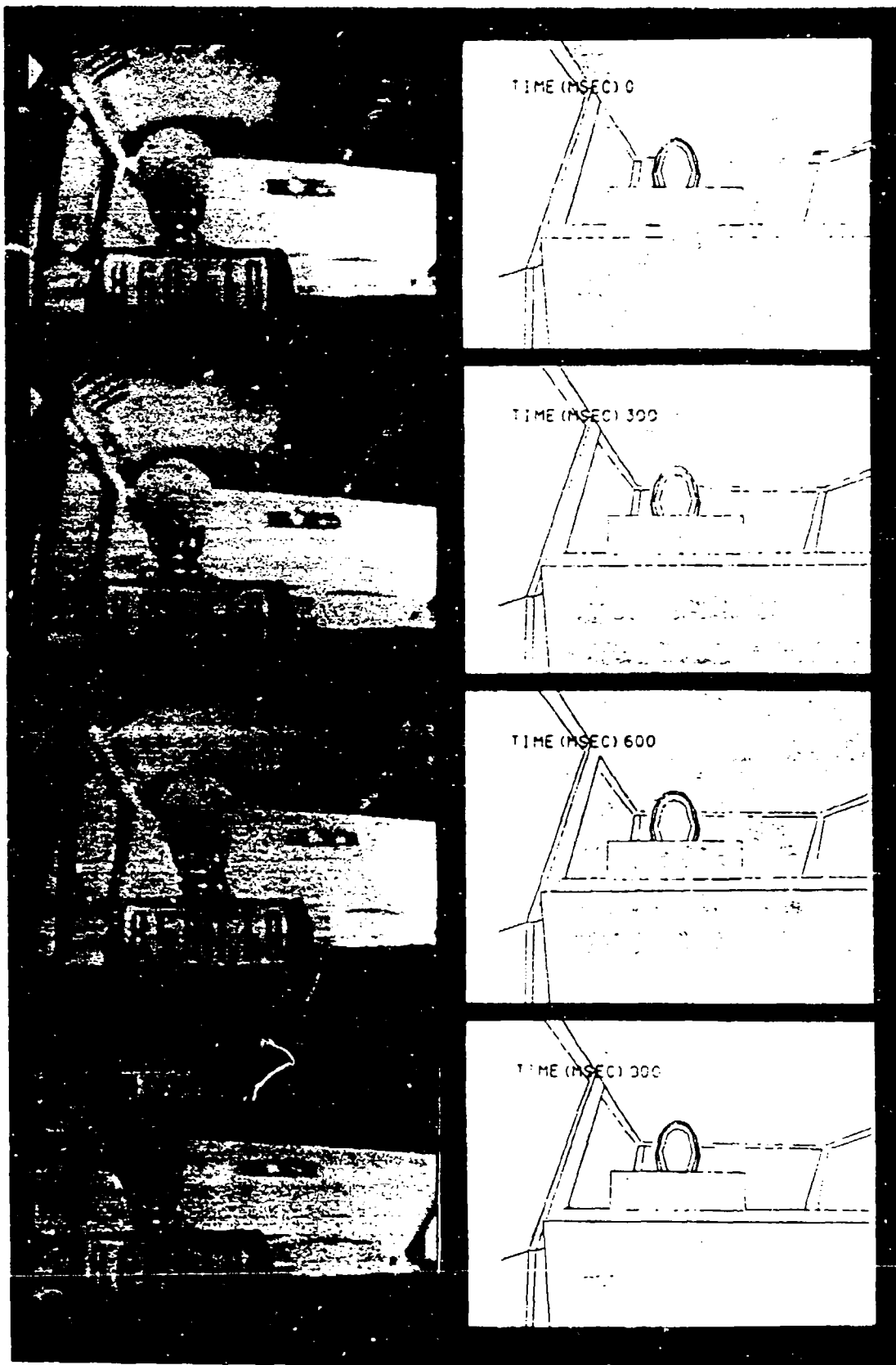


Figure 5 - Test No. 4, Celebrity
Test Film and Simulated Occupant Motion

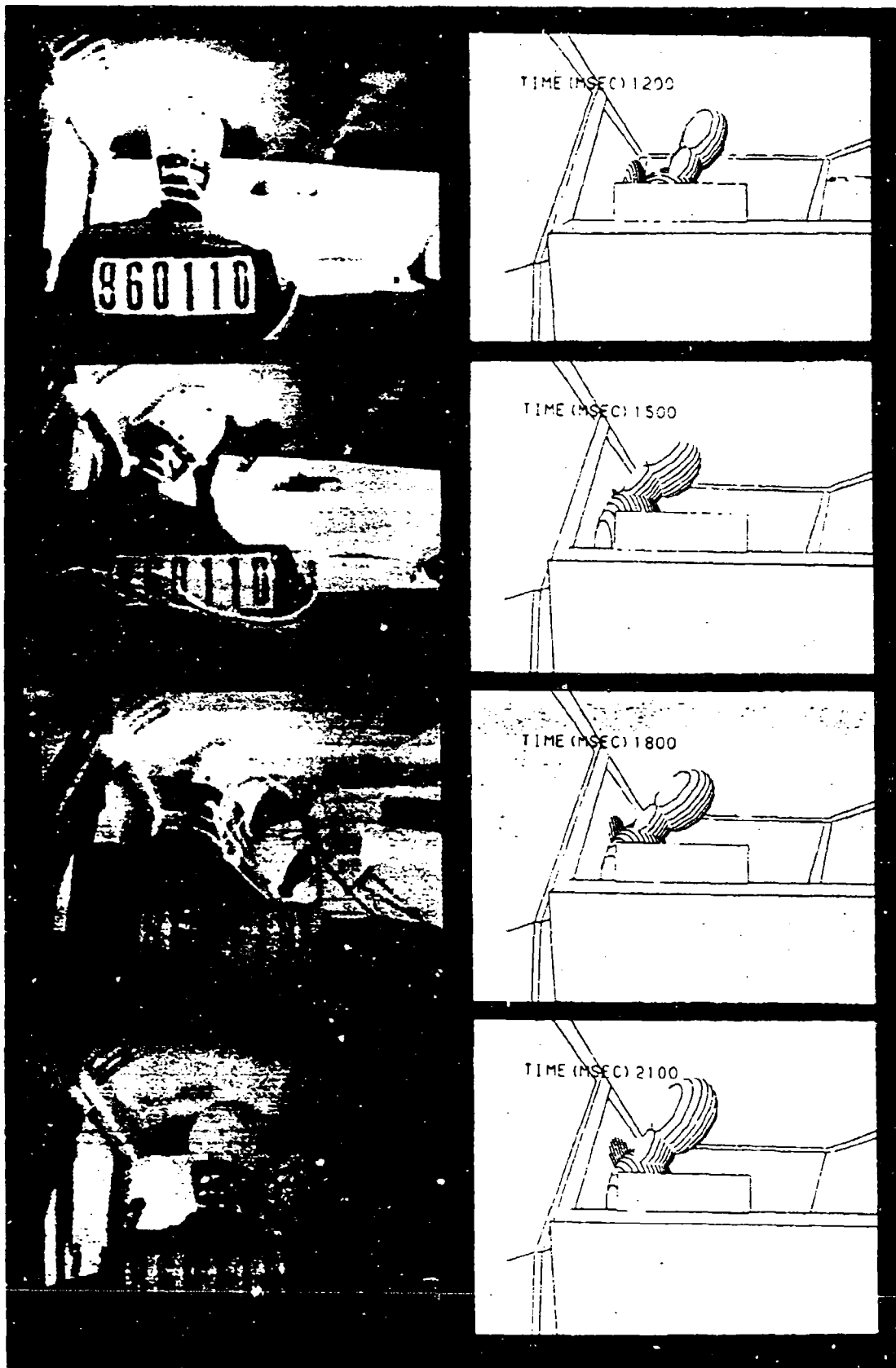


Figure 5 - continued

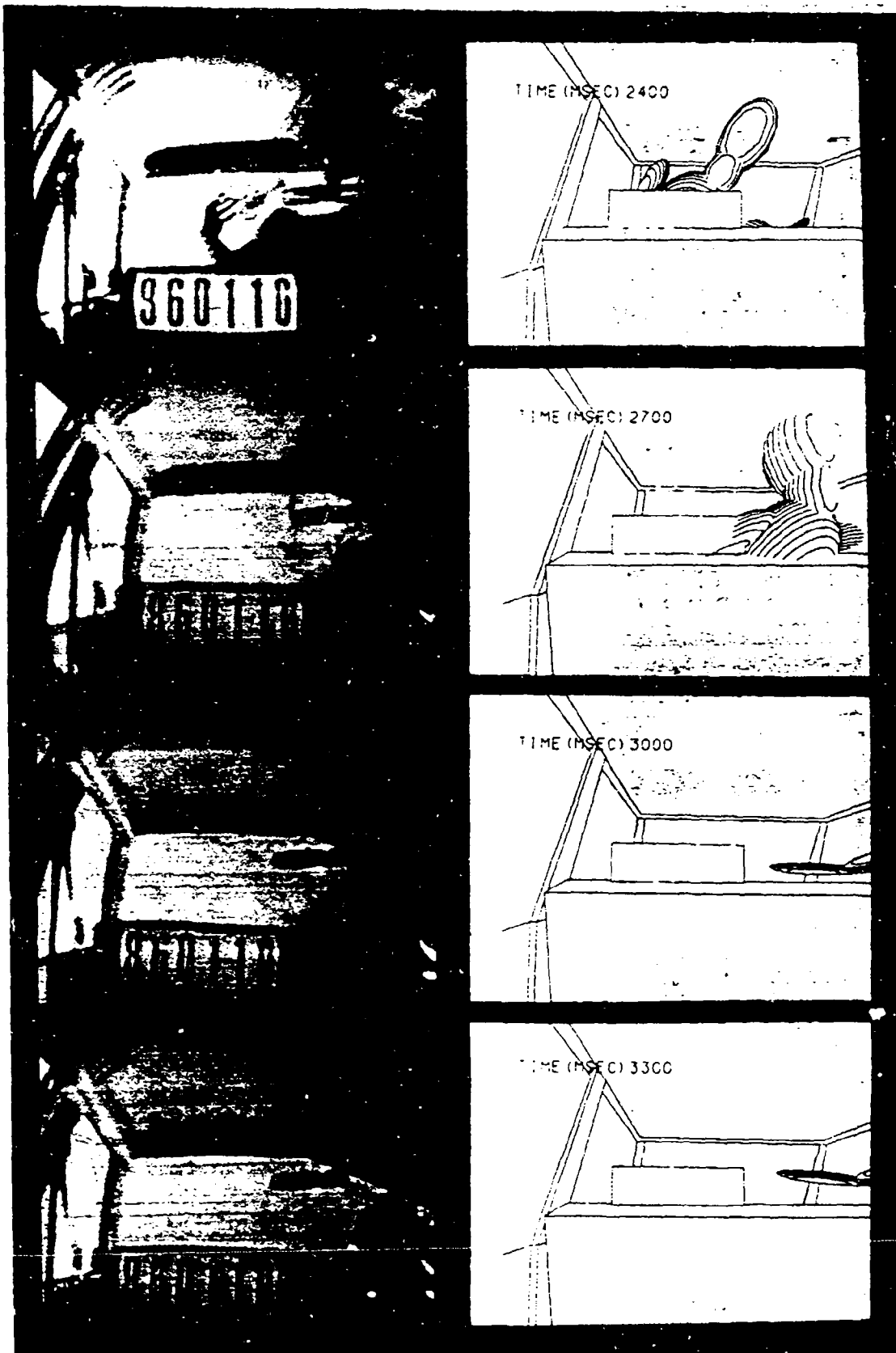


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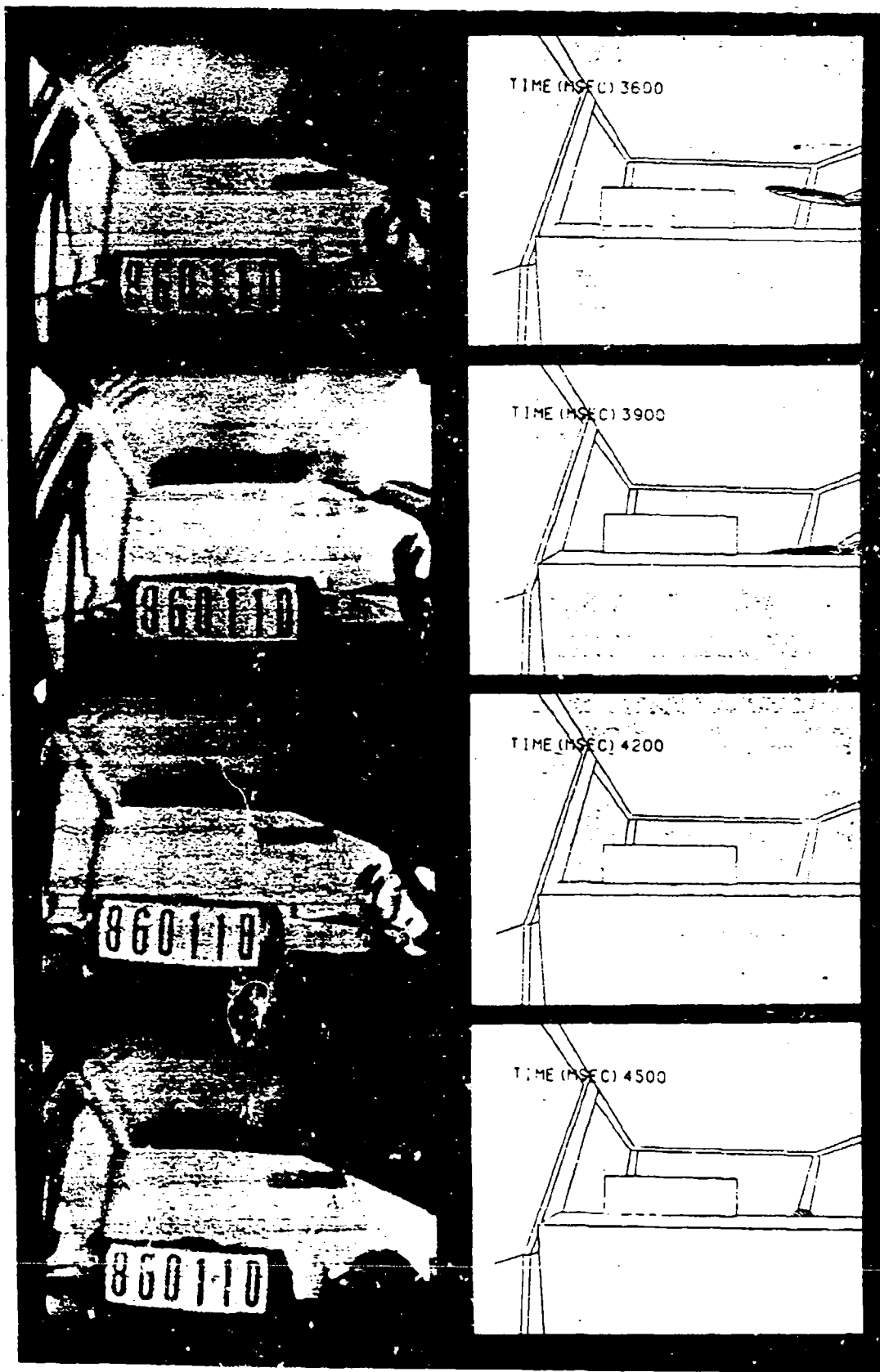


Figure 5 - continued

The simulated motion matches very well with the actual motion. The only major discrepancy occurs when the dummy bounces off the left side door. The simulation reacts more slowly than does the experimental dummy, indicating that the force-deflection functions for those contacts may not be stiff enough. Another contributing factor to this difference could be a result of the vehicle motion reconstruction process itself. The procedure used for reproducing the vehicle motion has the inherent effect of filtering out acceleration peaks which may lead to small phase shifts in the occupant motion. In spite of this inconsistency, the simulation is very good. At the 1500 msec mark, both the simulation graphics and the actual rollover test photographs show the head hitting the roof, the left shoulder and upper torso impacting the window, and the middle and lower torso segments impacting the door. As the dummy rebounds into the passenger side of the car, the body turns to face the left A-pillar, first in the experimental test and then in the simulation. The last one and one-half seconds of the test are very well matched, as demonstrated in Figure 5.

Transducer Time Histories

Triaxial accelerometers mounted in the head and upper torso and load cells mounted in the neck of the dummy measured the accelerations, forces, and torques, respectively, produced in these segments during the rollover tests. Corresponding quantities from the simulations were calculated by the ATB

model and are plotted with the experimental data. Figures 6 and 7 show these plots for the Celebrity test.

These comparisons clearly indicate that the simulation process was not able to accurately predict the internal dummy forces or accelerations. The best that can be said is that the magnitudes of the predicted responses are at least similar to the observed response magnitudes. Probably the two main reasons for the poor agreement are that simulated and observed body with vehicle contacts do not occur at the same time and the contact force-deflection characteristics used in the simulation do not precisely represent the body segment and vehicle contact surface compliance properties. The first problem is due to slight differences in predicted and observed motion which result in the body contacting the interior surfaces at slightly different times. The specification of an improper force-deflection characteristic will not generally modify gross body motion substantially, but it will change the profile of the contact force and the resulting local acceleration. Generally, a more compliant force-deflection characteristic will result in a lower peak contact force of longer duration. A stiffer characteristic will produce a higher peak and shorter duration contact force. The observed gross motion may not, however, be perceptibly different.

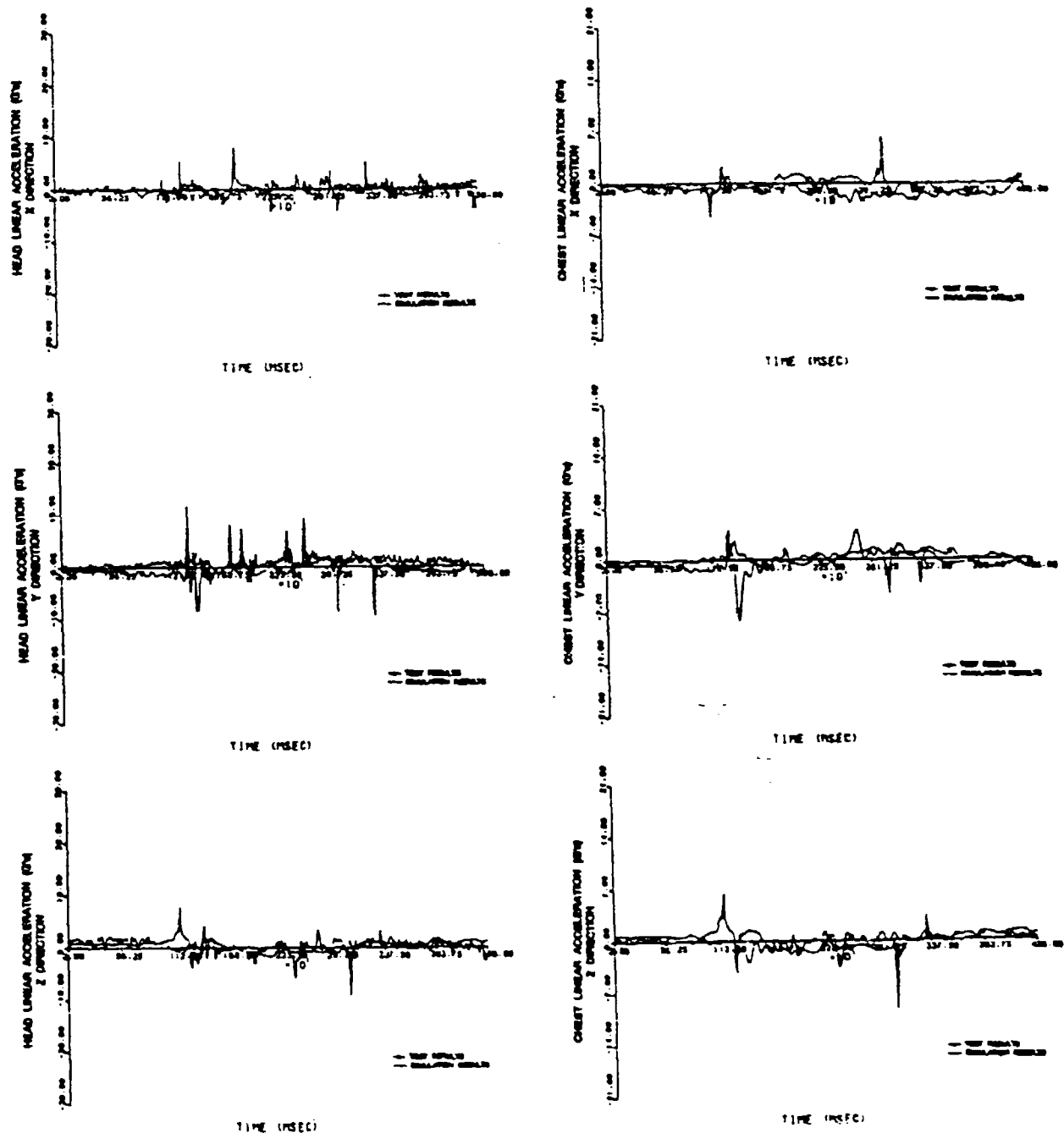


Figure 6 - Test No. 4, Celebrity
Head and Chest Tri-axial Accelerometer Data From The Test and
ATB Occupant Simulation

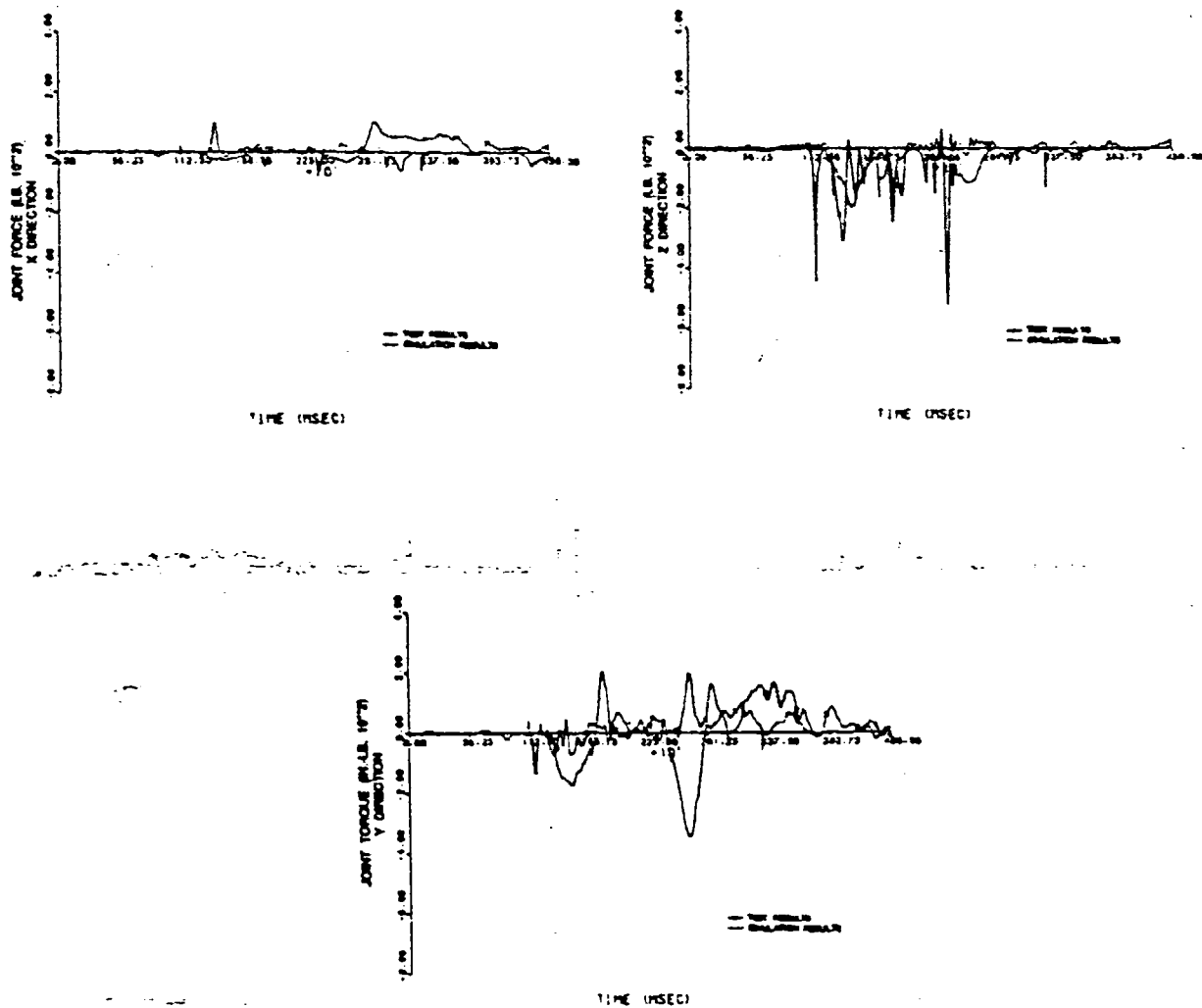


Figure 7 - Test No. 4, Celebrity
Neck Load Cell Data From Test and ATB Occupant Simulation

SUMMARY

The purpose of this program was to refine and further validate the methodology for using the ATB model to simulate occupant motion during rollover crashes. Five rollover tests were successfully simulated, demonstrating the capability of the model to simulate complex rollover crashes for belt restrained and unrestrained occupants, and its value as a tool in studying occupant motion during rollover.

It was found that the testing configuration created some problems in accurately simulating the occupant motion. In particular, the method of maintaining the dummy in an upright position until the vehicle was released was inconsistent, making it difficult to know how the string affected the initial dummy motion. Some of the differences between the initial test and simulated motion are most likely due to this problem since, if the initial motion is not well defined, subsequent motion is modified. It is recommended that in future tests a more reliable method be used for initially restraining the dummy.

An accurate prescription of the vehicle motion was also found to be very important for accurate predictions of the dummy's motion. Although the reconstruction process was refined for this study, it is still a tedious task to digitize locations

and orientations frame by frame. This process can be improved by the use of graphics workstations with image overlaying that are currently available.

An option added to the ATB model allowing the prescription of the motion of the roof with respect to the vehicle would allow the model to simulate rollover tests with structural intrusions. A method of determining the roof motion from the test films would also have to be developed, but this capability would expand the applicability of the model to many crash situations where intrusions to the vehicle interior affect the occupant.

The simulated dummy kinematics of each of the tests agreed well with the observed test kinematics considering the complexity of the rollover motion and the length of the simulations. Most of the inconsistencies can be attributed to the vehicle motion reconstruction process. In general the ATB model was able to effectively simulate the dummy motion in the tests. The success of these simulations and the earlier guardrail impact rollover simulation demonstrate the capability to predict occupant dynamics during rollover crashes. These studies show that the methodology of using the ATB model to predict occupant motion has developed into a useful tool for rollover research, especially in investigating the effectiveness of restraint system and vehicle padding modifications in preventing ejection and mitigating injury.

The input data sets for each of the six ATB occupant simulations are voluminous. Therefore they have not been included in this report. Much of the input is the same as that printed in Reference 5. The specific simulation input data for these simulations is available from the authors at:

Armstrong Aerospace Medical Research Laboratory

Modeling and Analysis Branch (AAMRL/BBM)

Wright-Patterson AFB OH 45433-6573.

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APPENDIX

TEST NO. 2 - PLYMOUTH RELIANT

In this test, the vehicle is initially yawed 42 degrees, rolled 41 degrees, and has an initial velocity of 21 mph. After release, the car rolls one and one-half times, and stops on its roof. The Part 572 occupant dummy is seated in the driver's seat and is restrained with a 3-point belt. Figure 8 contains the vehicle positions from the film and reconstructed motion at 600 msec. intervals. In Figure 9, the plots of the vehicle accelerometer and rate gyro data are shown. Both figures indicate that the reconstructed vehicle motion compares quite well with the actual vehicle motion. The film and simulated occupant motion is shown in Figure 10. It is clear that the simulation matches very well with the actual motion. The torso motion is especially good, except that the simulated dummy tends to move with greater lateral displacements than does the test dummy. This can be attributed to differences in the stress-strain characteristics of the seatbelt. Figure 11 shows the head and chest accelerometer data from this test. As with the Celebrity data, it is very difficult to derive much meaningful information from these plots, except to show that the magnitudes are of the same order.

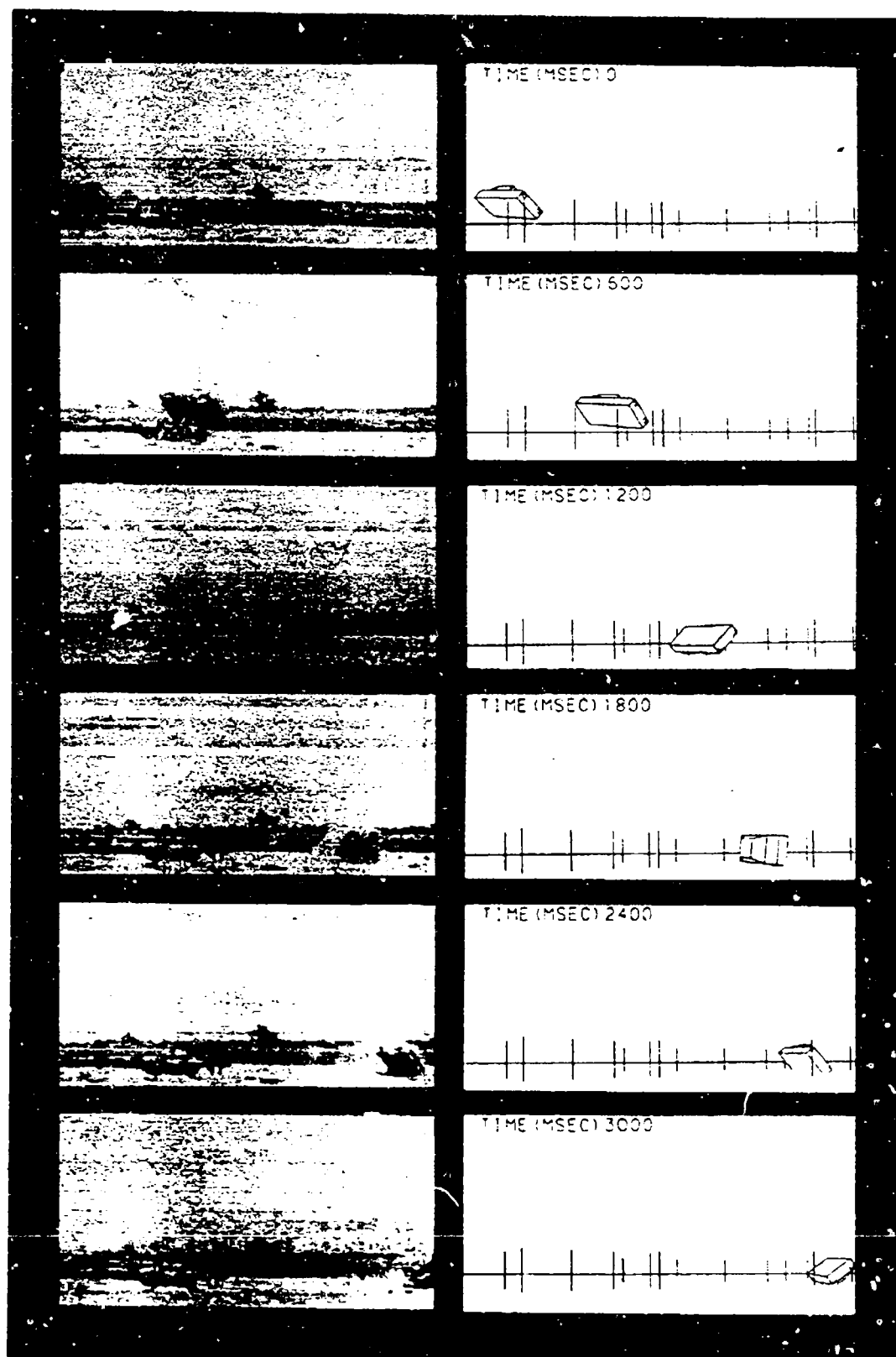


Figure 8 - Test No. 2, Reliant
Test Film and Reconstructed Vehicle Motion

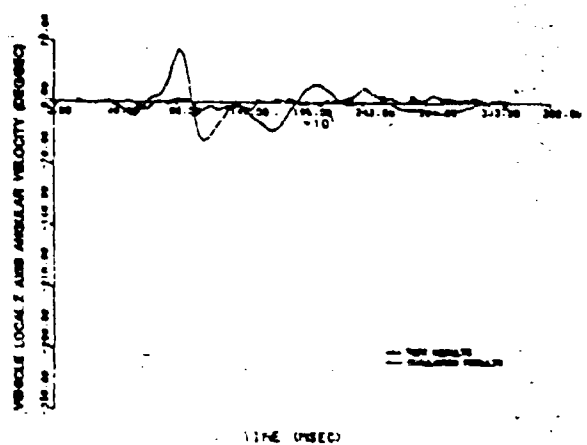
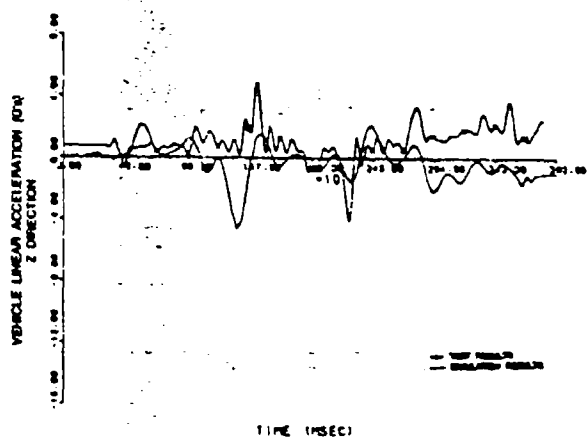
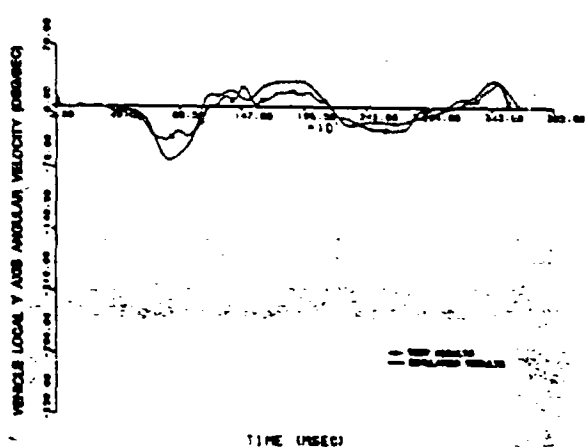
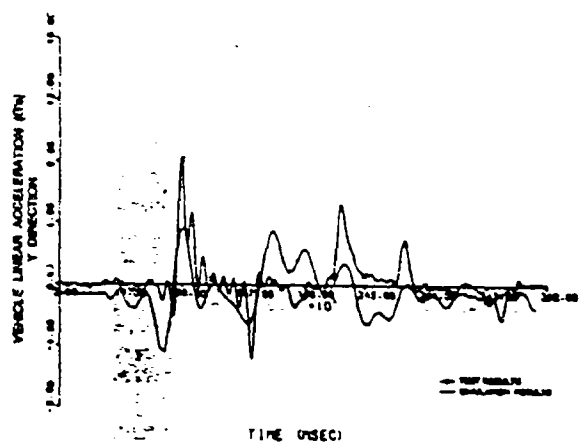
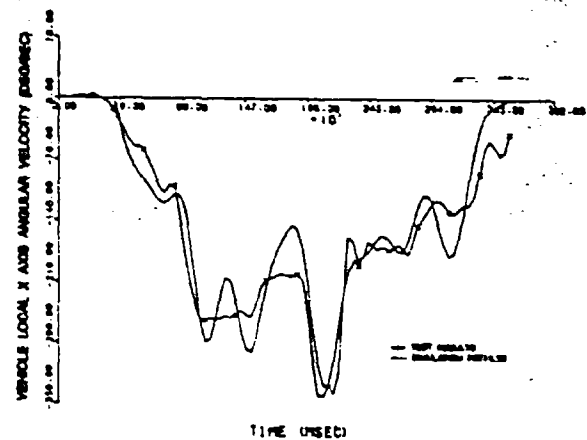
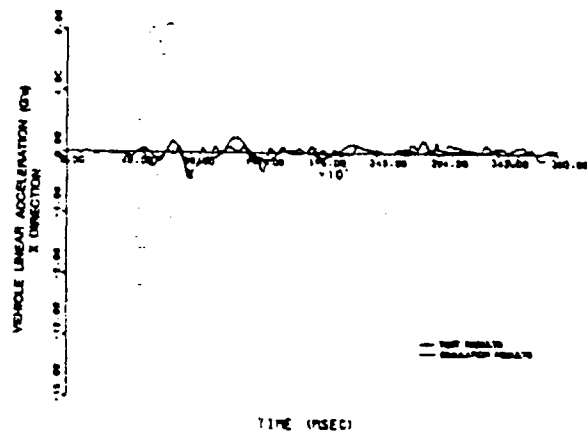


Figure 9 - Test No. 2, Reliant
Vehicle Tri-axial Accelerometer and Angular Rate Gyro Data
From Test and Reconstructed Motion

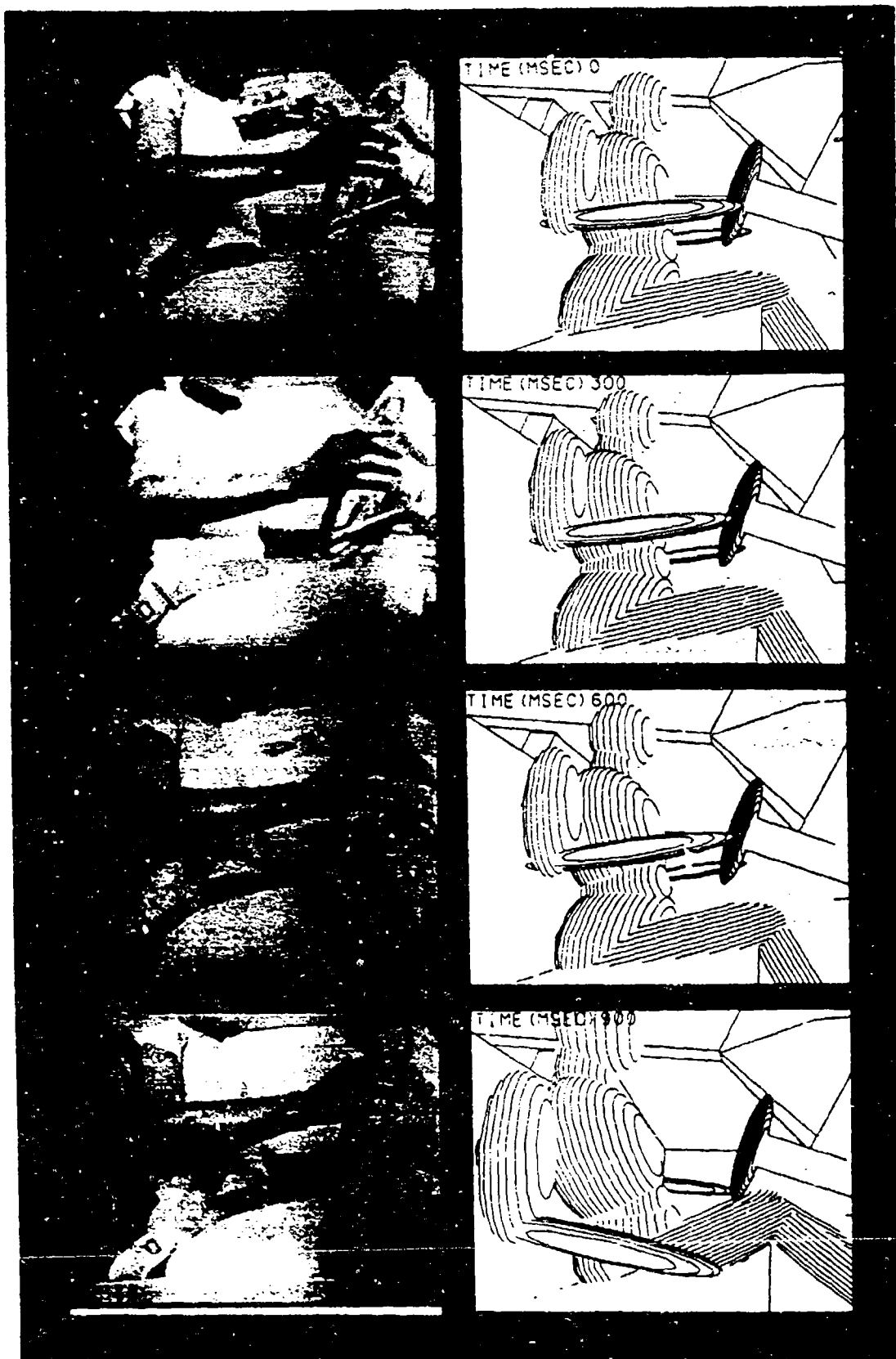


Figure 10 - Test No. 2, Reliant
Test Film and Simulated Occupant Motion

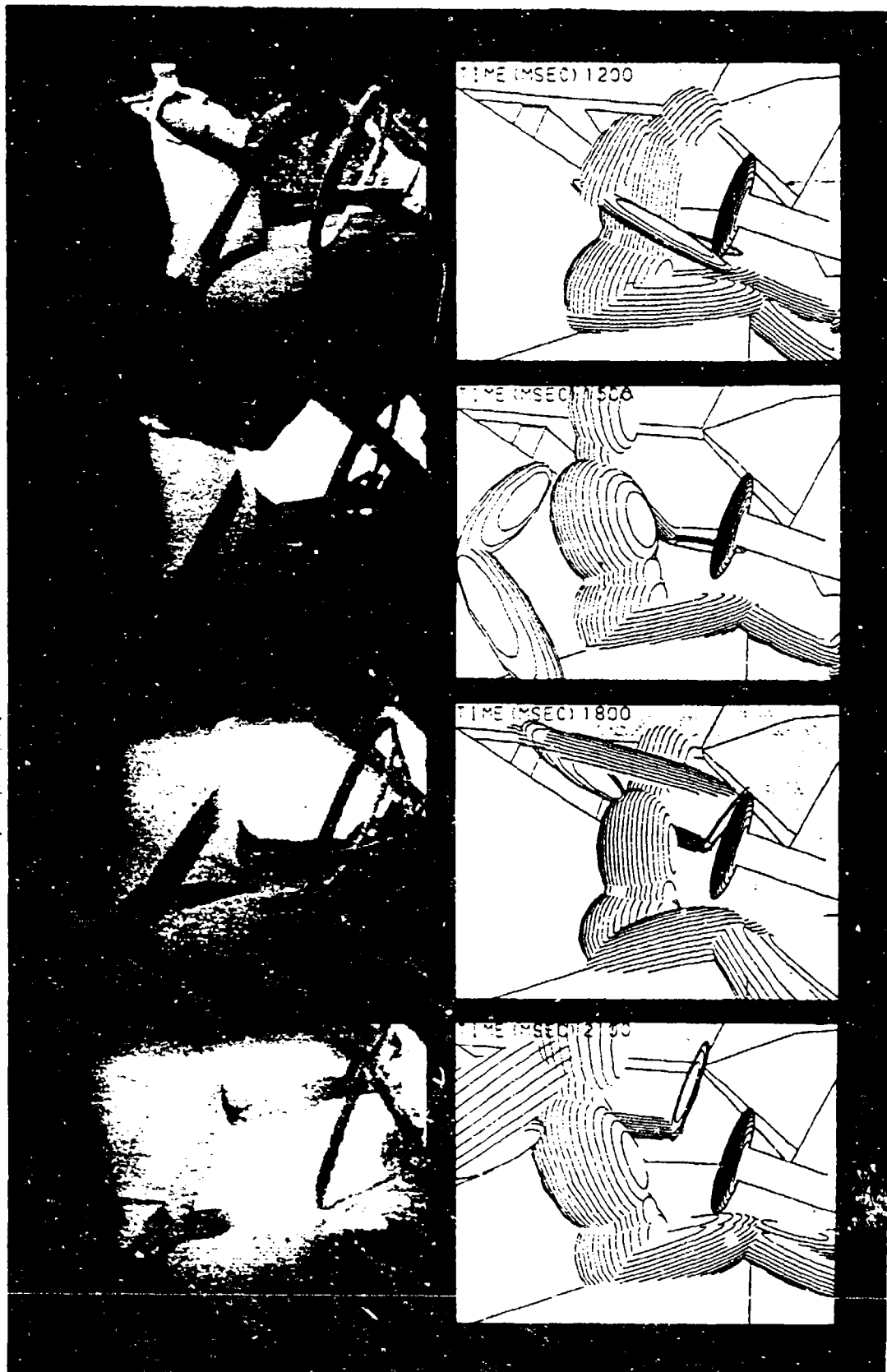


Figure 10 - continued

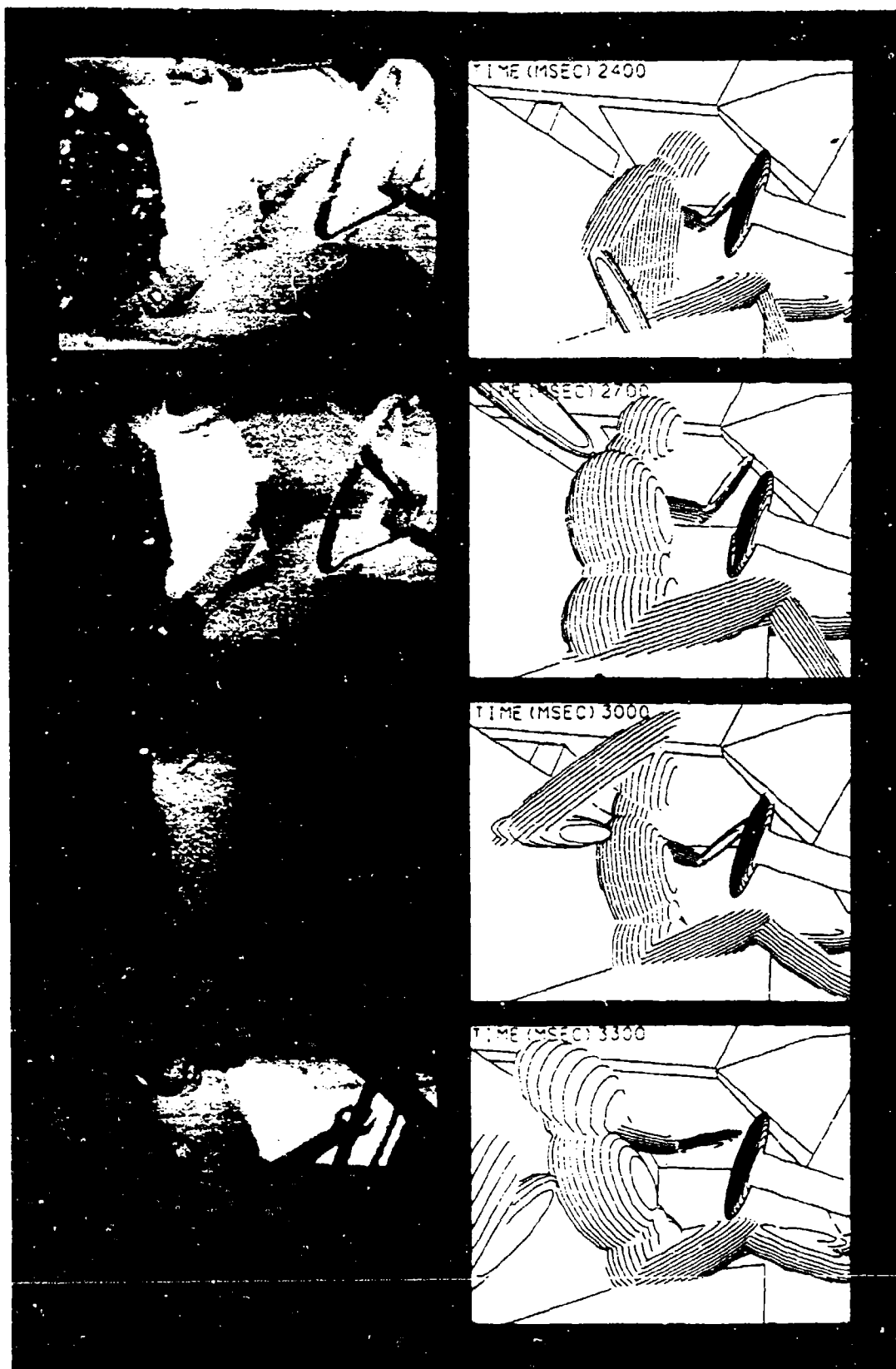
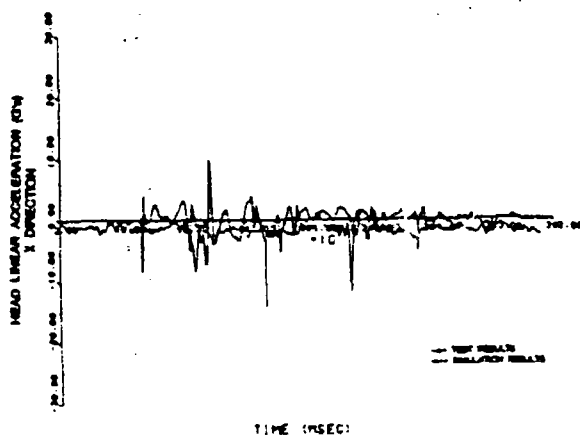
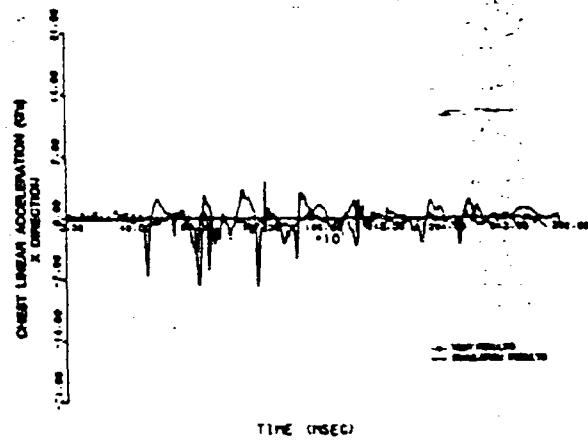


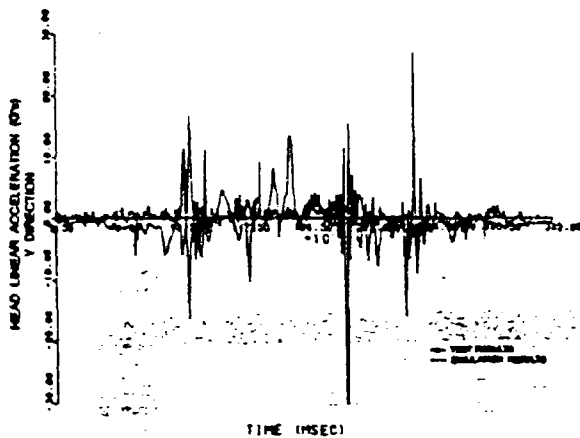
Figure 10 - continued



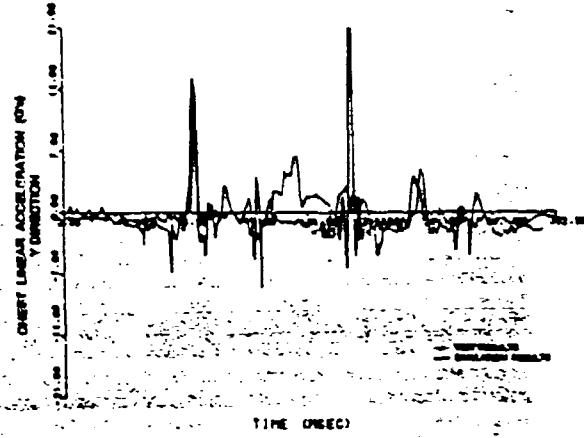
TIME (msec)



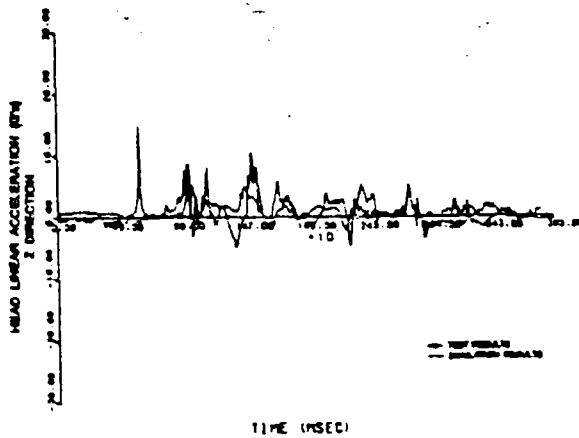
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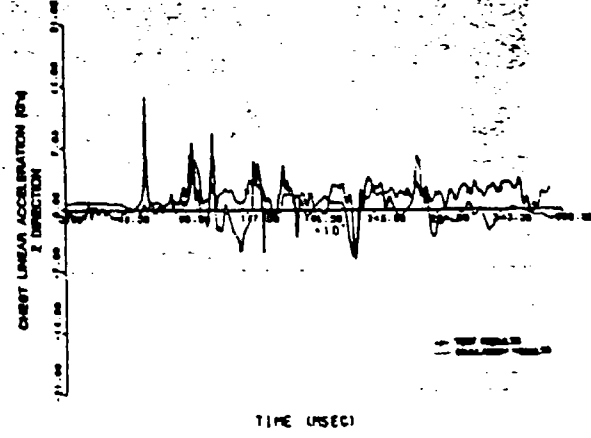
TIME (msec)



TIME (msec)



TIME (msec)



TIME (msec)

Figure 11 - Test No. 2, Reliant
Head and Chest Tri-axial Accelerometer Data From The Test and
ATB Occupant Simulation

TEST NO. 3 - HONDA ACCORD

This test uses a 1984 Honda Accord which is initially yawed 44 degrees, rolled 36 degrees, and given an initial velocity of 21 mph. The vehicle rolls one-half revolution upon release and ends up on its roof. An unrestrained Part 572 dummy is placed in the driver's seat. The film and reconstructed vehicle motion is shown in Figure 12 and plots of the vehicle accelerometer and rate gyro data comparisons are shown in Figure 13. The agreement is good, but the X-axis angular velocity plot shows that either the rate gyro or its data line was not working correctly. A comparison of the film and simulated occupant motion is in Figure 14. This occupant simulation agrees quite well with the actual dummy motion, as they both impact the driver's door and then, as the car rolls onto its roof, come out of the seats, rotate, and fall against their backs onto the ceiling. The simulation is stopped at 2400 msec because the vehicle's roof crushed at this time. Figure 15 shows the plots of the head and chest accelerometer data from both the experiment and the simulation. As with the previous tests, it is difficult to make any concrete conclusions from the accelerometer data.

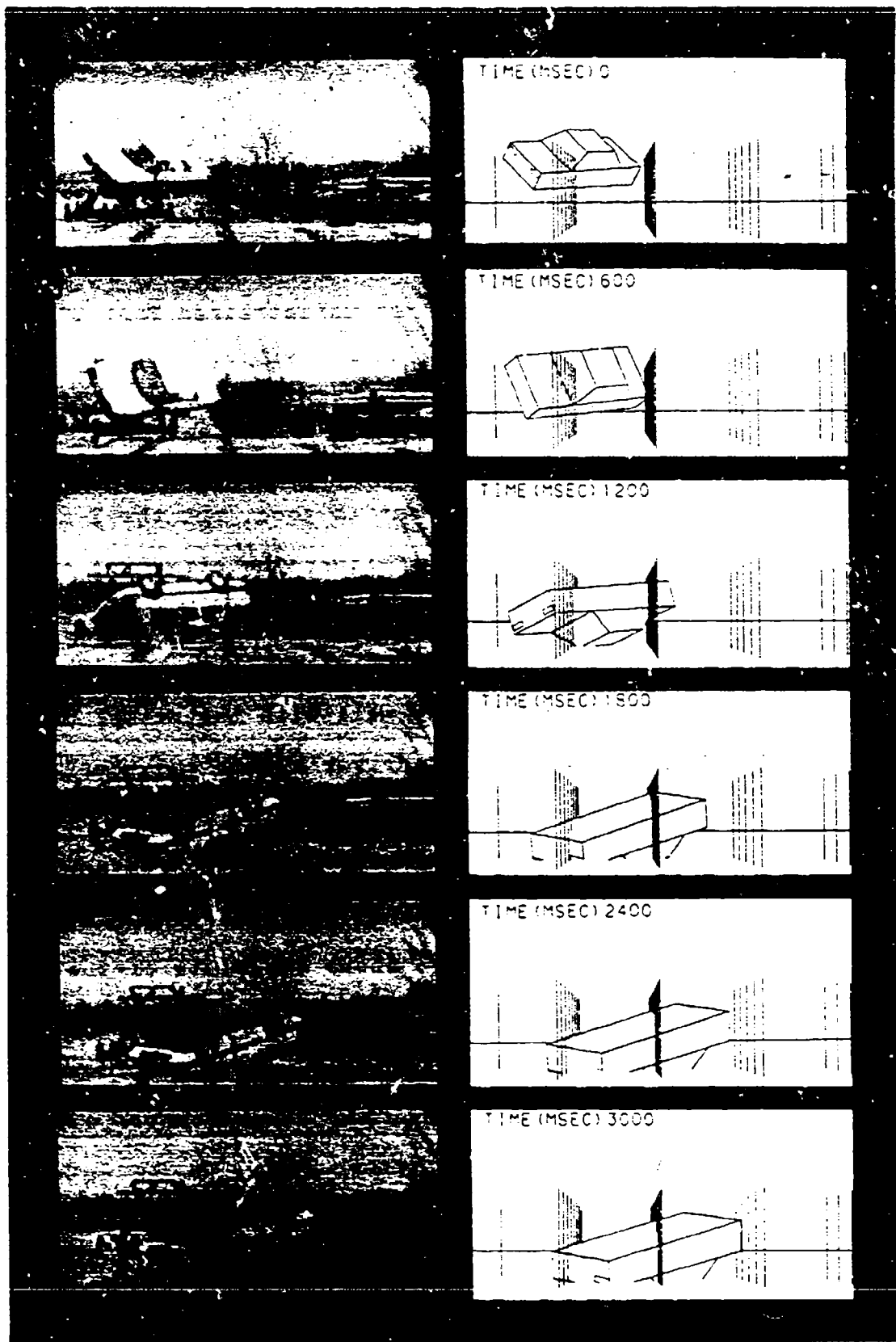


Figure 12 - Test No. 3, Accord
Test Film and Reconstructed Vehicle Motion

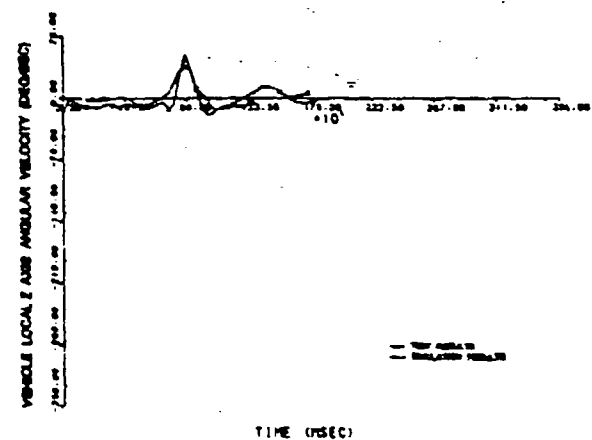
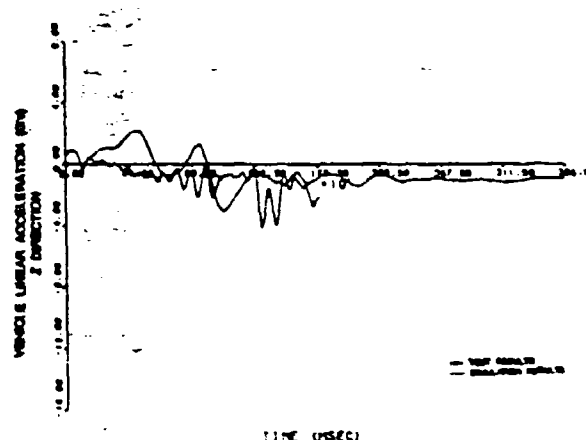
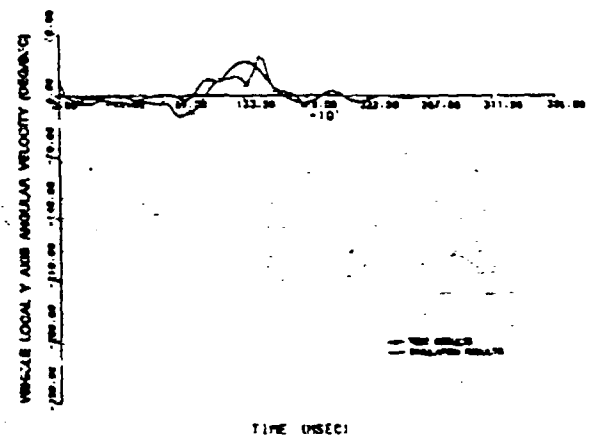
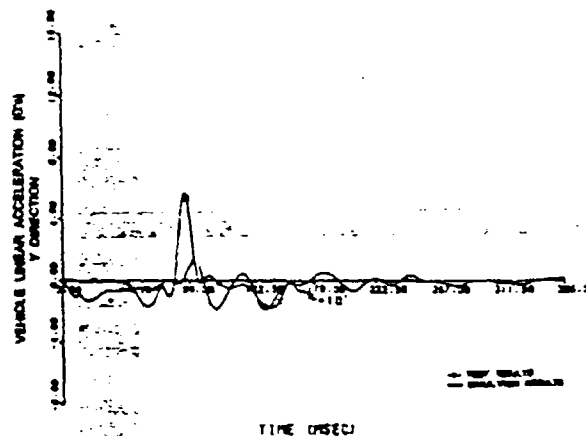
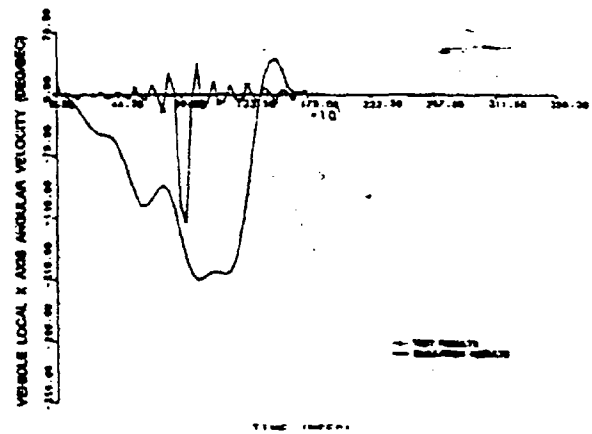
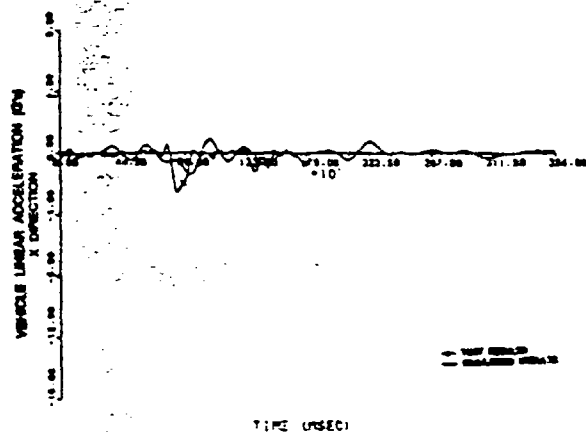


Figure 13 - Test No. 3, Accord
Vehicle Tri-axial Accelerometer and Angular Rate Gyro Data
From Test and Reconstructed Motion

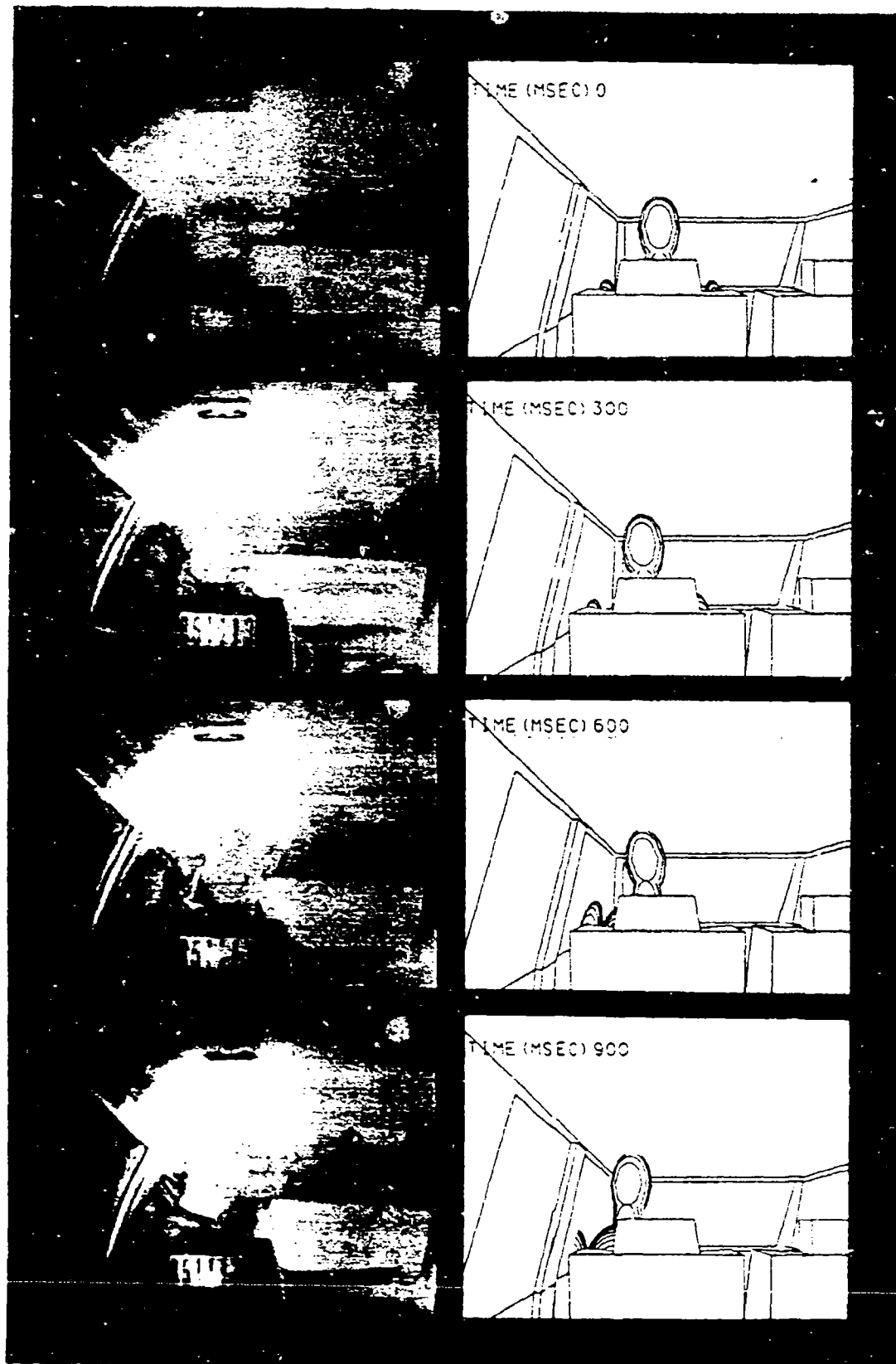


Figure 14 - Test No. 3, Accord
Test Film and Simulated Occupant Motion

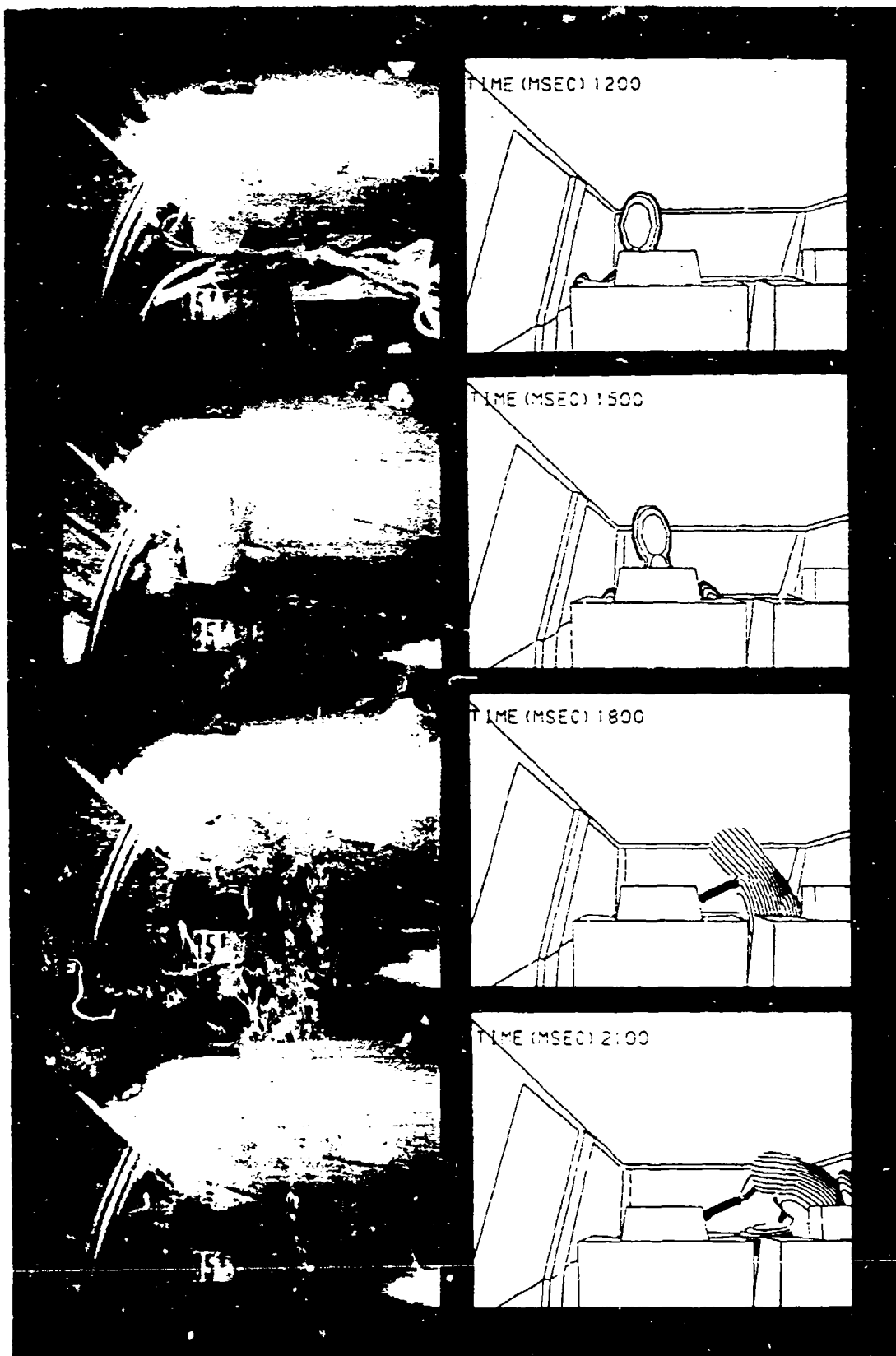


Figure 14 - continued

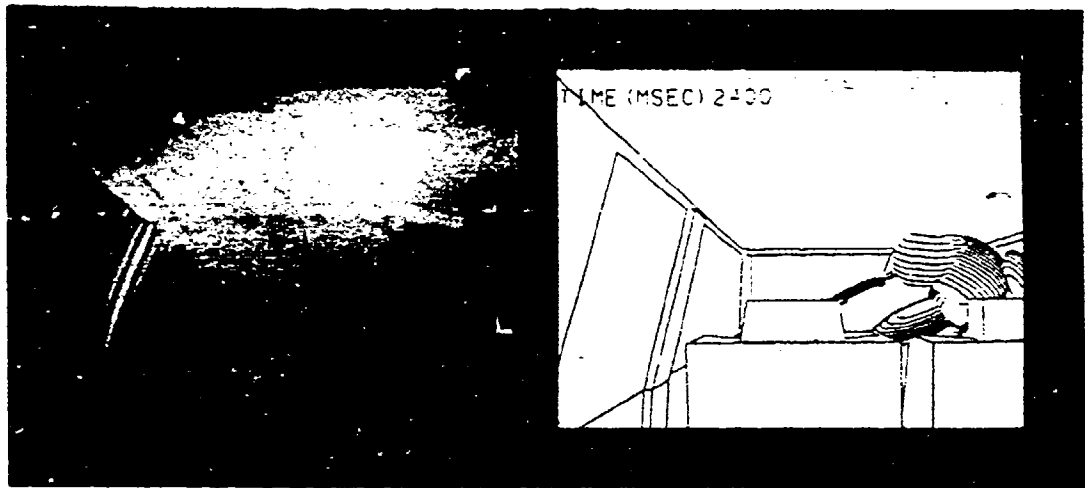


Figure 14 - continued

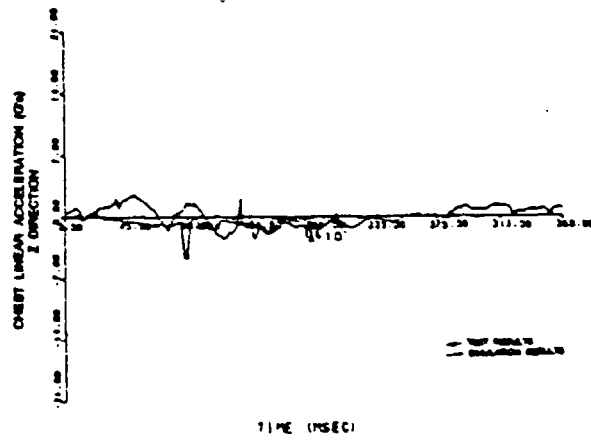
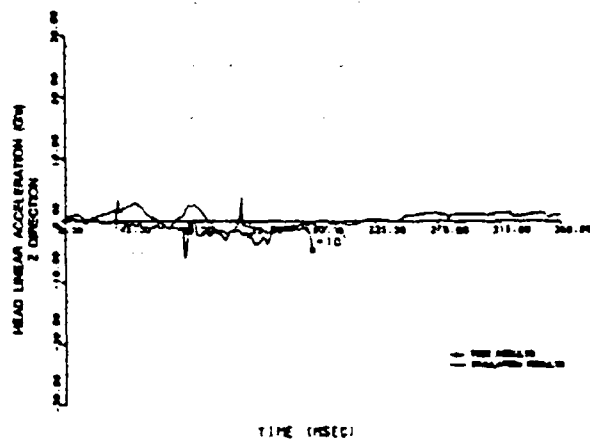
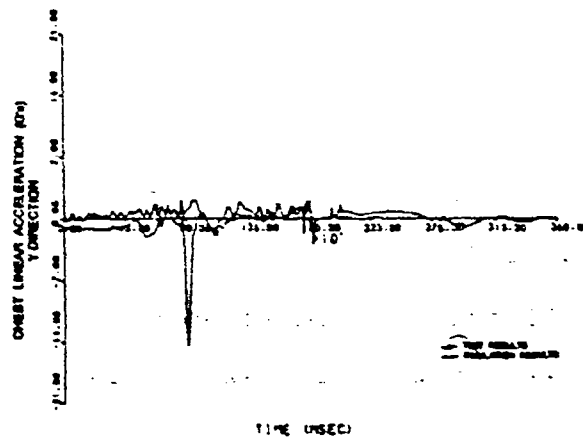
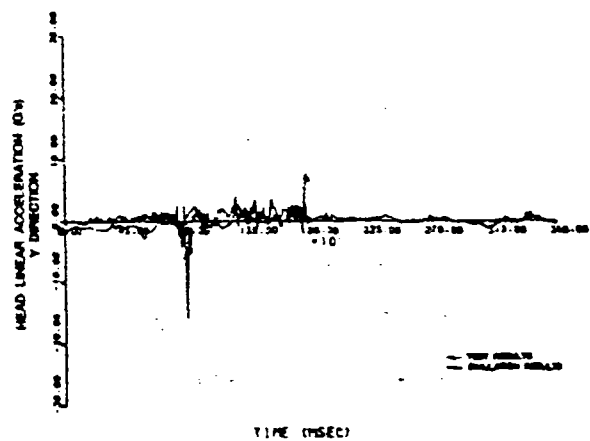
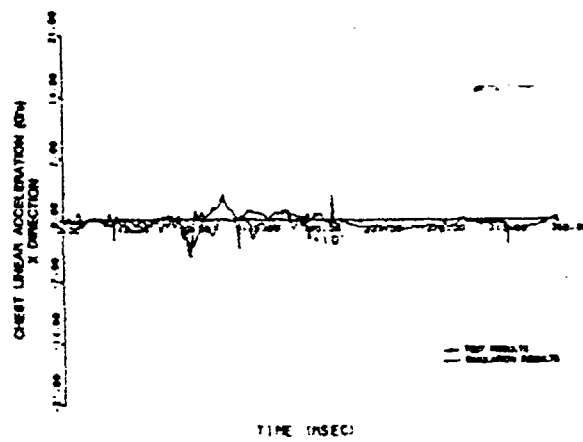


Figure 15 - Test No. 3, Accord
Head and Chest Tri-axial Accelerometer Data From The Test and
ATB Occupant Simulation

TEST NO. 5 - DODGE OMNI

The vehicle used in this test is a 1979 Dodge Omni, which has an initial orientation of 45 degrees yaw and 39 degrees roll. It is given a velocity of 23 mph and, when released, rolls one-half revolution, stopping on its roof. For this test, an unrestrained Hybrid III dummy is placed in the front passenger seat. The film and reconstructed vehicle motion is presented in Figure 16 and the vehicle accelerometer and rate gyro data is shown in Figure 17. These figures illustrate that the reconstructed vehicle motion matches quite well with the actual car motion. The film and simulated occupant motion is shown in Figure 18. The occupant simulation is stopped at 1200 msec. During the test, the vehicle roof collapsed and impacted with the dummy after 1200 msec. Up until this time, the agreement is fairly good, with both dummies leaning toward the right side at 600 msec and then sliding up and off the seat. This motion is due, as discussed previously, to the force of the string that joins the dummy to the car door. The head and chest accelerometer data is shown in Figure 19, and the neck load cell data is shown in Figure 20. These plots illustrate the effect of including the 'string' in the simulation, as discussed in the section on the initial balancing of the dummies.

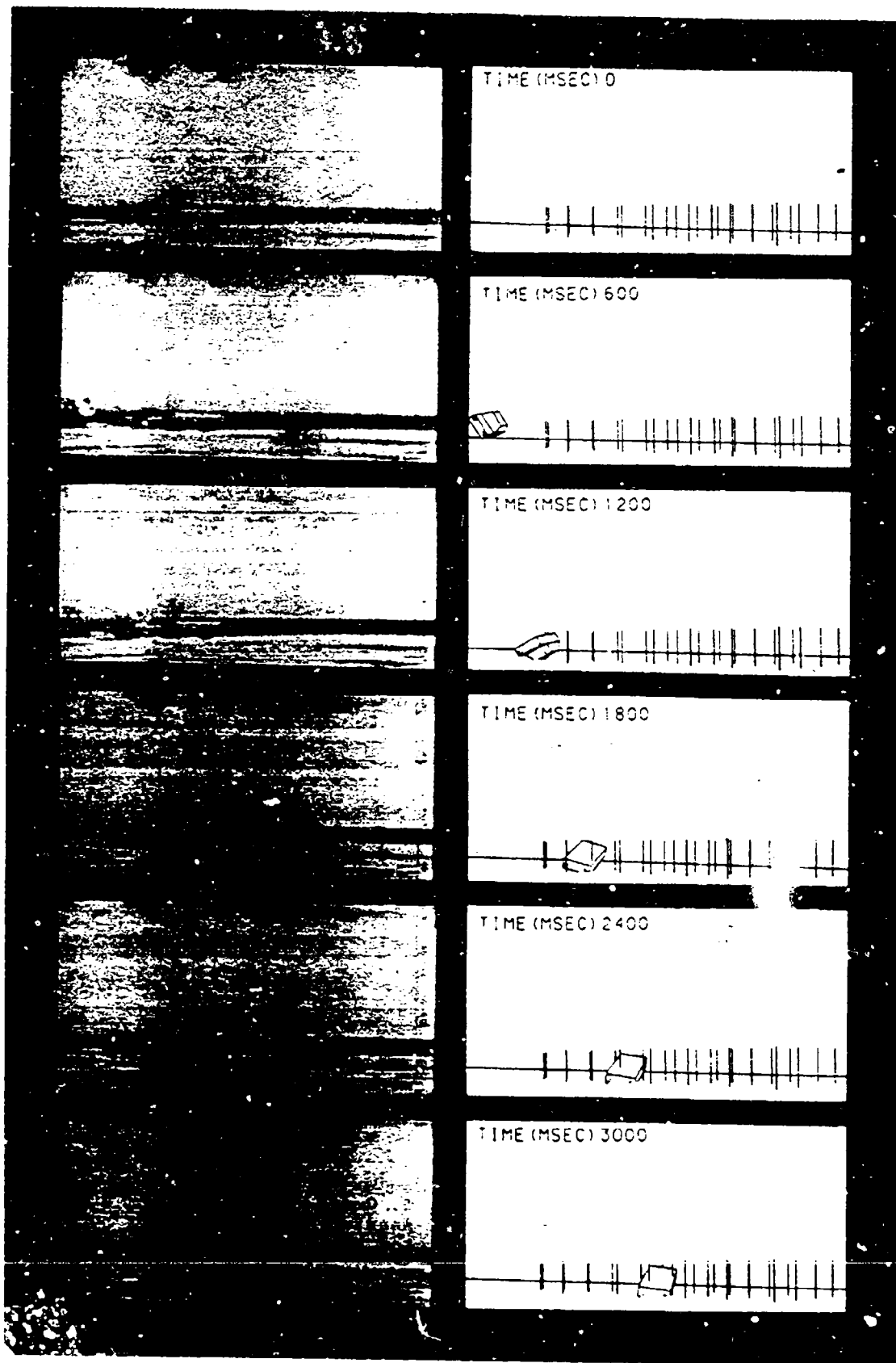


Figure 16 - Test No. 5, Omni
Test Film and Reconstructed Vehicle Motion

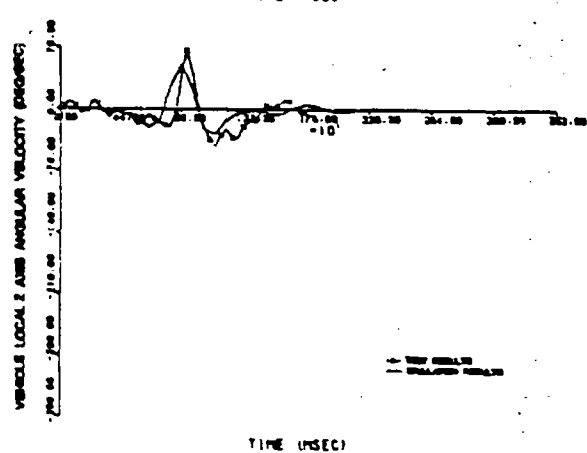
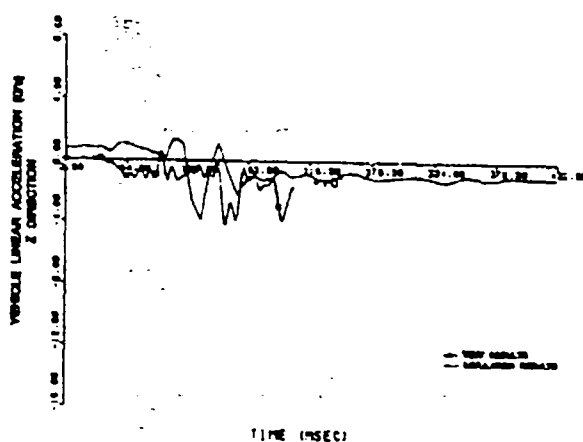
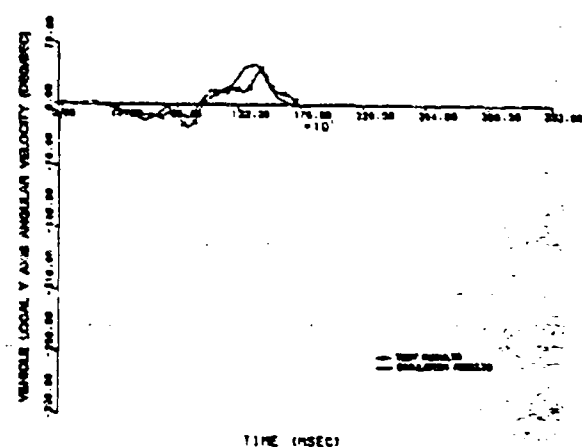
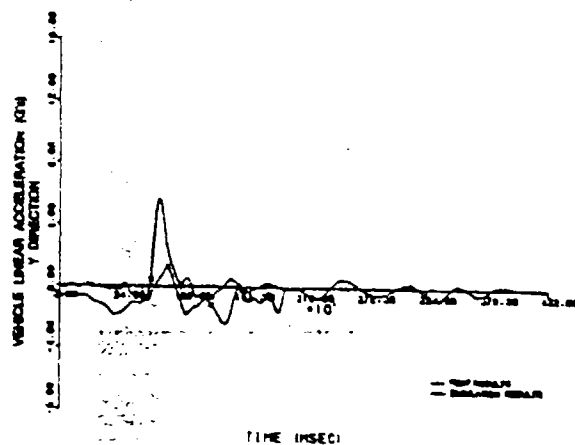
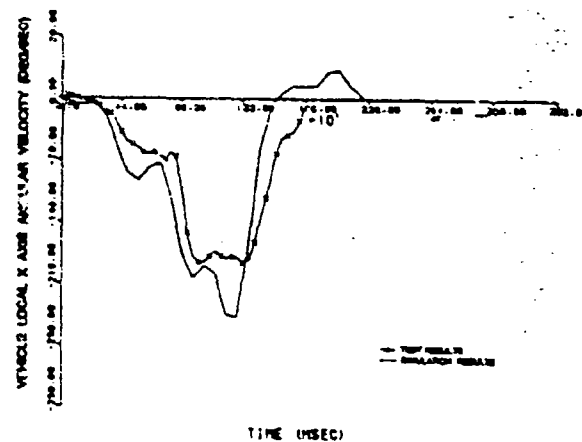
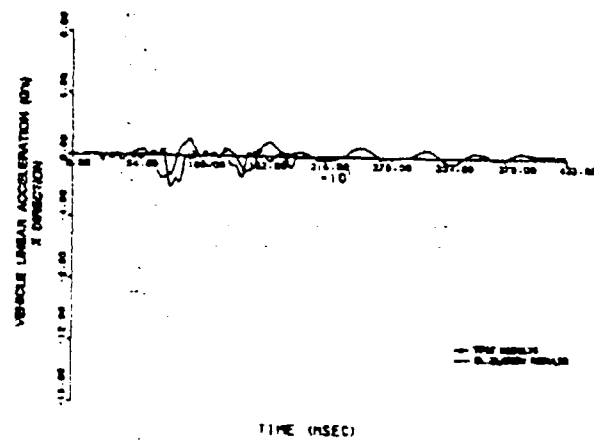


Figure 17 - Test No. 5, Omni
Vehicle Tri-axial Accelerometer and Angular Rate Gyro Data
From Test and Reconstructed Motion

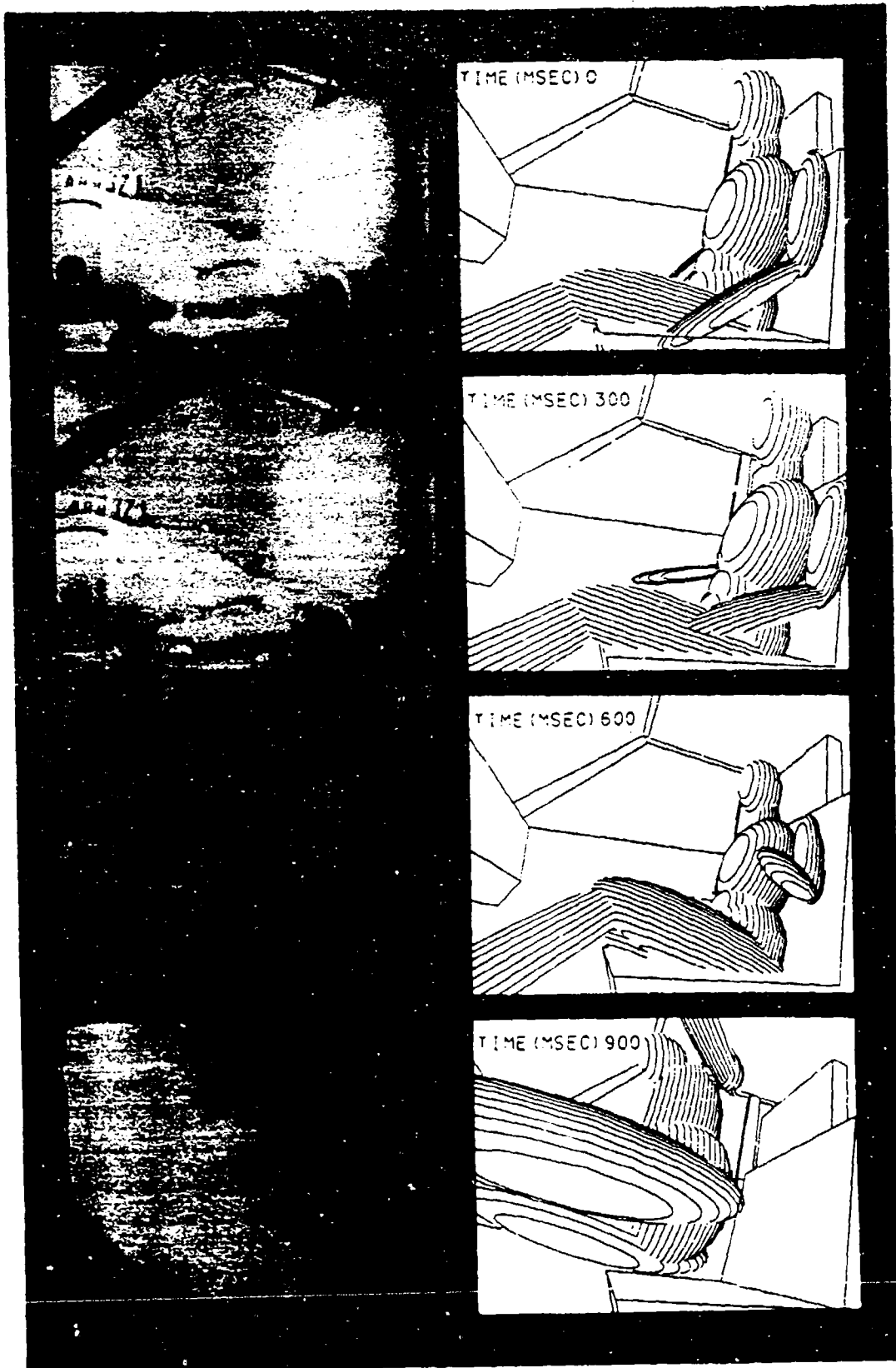


Figure 18 - Test No. 5, Omni
Test Film and Simulated Occupant Motion

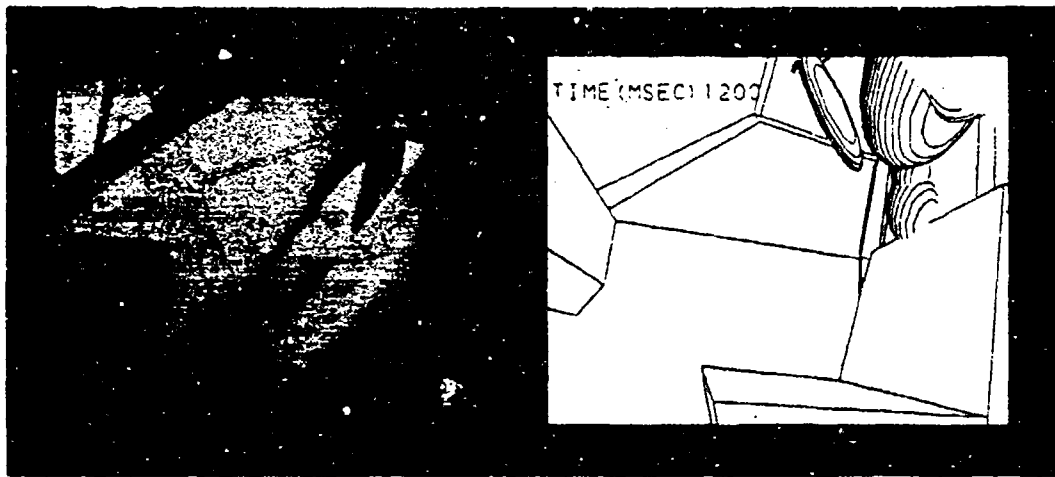


Figure 18 - continued

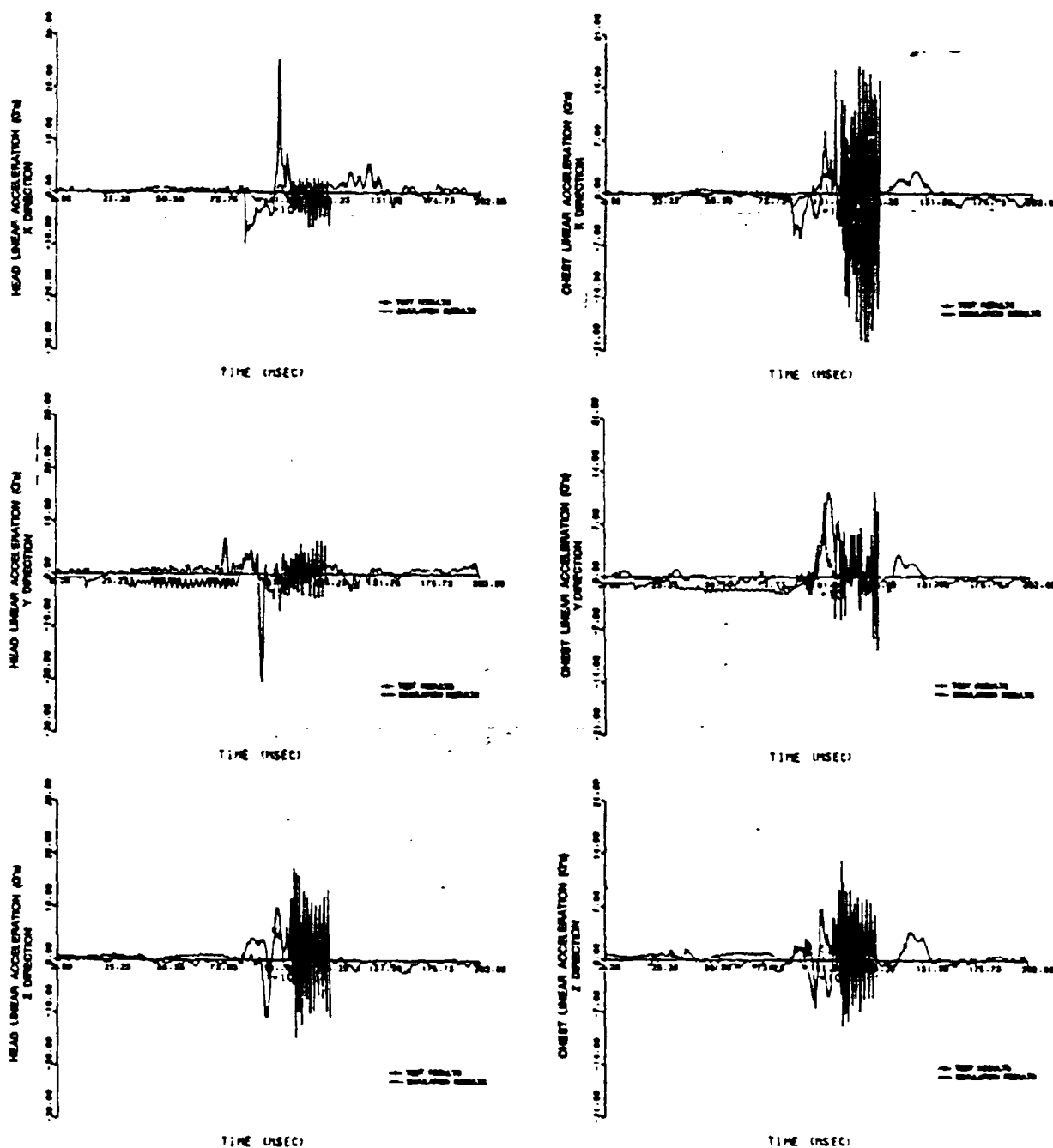
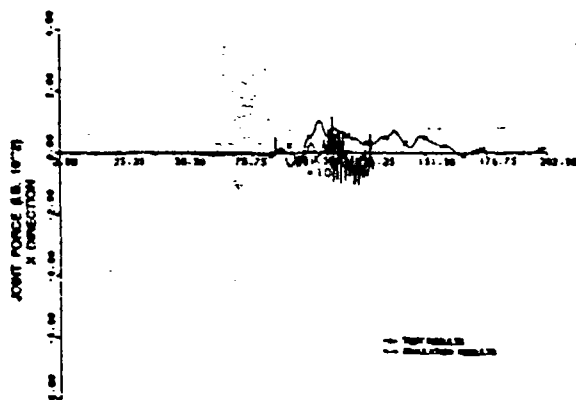


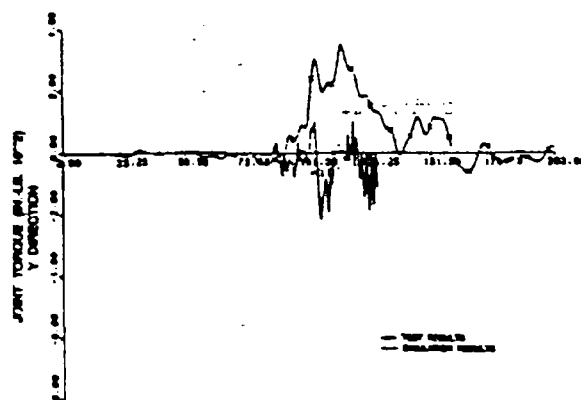
Figure 10 - Test No. 5. Omni
Head and Chest Tri-axial Accelerometer Data From The Test and
ATB Occupant Simulation



TIME (MSEC)



TIME (MSEC)



TIME (MSEC)

Figure 20 - Test No. 5, Omni
Neck Load Cell Data From Test and ATB Occupant Simulation

TEST NO. 6 - MERCURY ZEPHYR

The sixth test uses a 1982 Mercury Zephyr in which a Hybrid III dummy is seated unrestrained in the front passenger seat. The vehicle, initially oriented at 60 degrees yaw and 35 degrees roll and with an initial velocity of 23 mph, rolls one-half revolution and lands on its roof. Figure 21 contains the film and reconstructed vehicle motion, while Figure 22 presents the vehicle accelerometer and rate gyro data. As with the previous tests, there is no visible difference in the vehicles' motions and the data plots agree reasonably well. The only significant difference is in the yaw rate gyro data. This discrepancy may help explain the difference between the film and simulation occupant motion, which is shown in Figure 23. For the first 900 msec, the vehicle is simply being towed along the track and so the dummies have little motion. Starting at 1200 msec, a major difference becomes apparent. The simulated dummy slides along the bench seat to the driver's side with little angular motion, while in the actual test, the dummy topples over onto its left side. They both subsequently fall onto the vehicle's roof as the car becomes inverted. There is one major problem with this particular test which probably accounts for this disagreement. Because of a malfunction in a triggering system, the films of the actual vehicle motion, which are used to define the reconstructed vehicle motion, have no marks to indicate time zero. Therefore, it is not possible to precisely synchronize the linear and angular displacements as

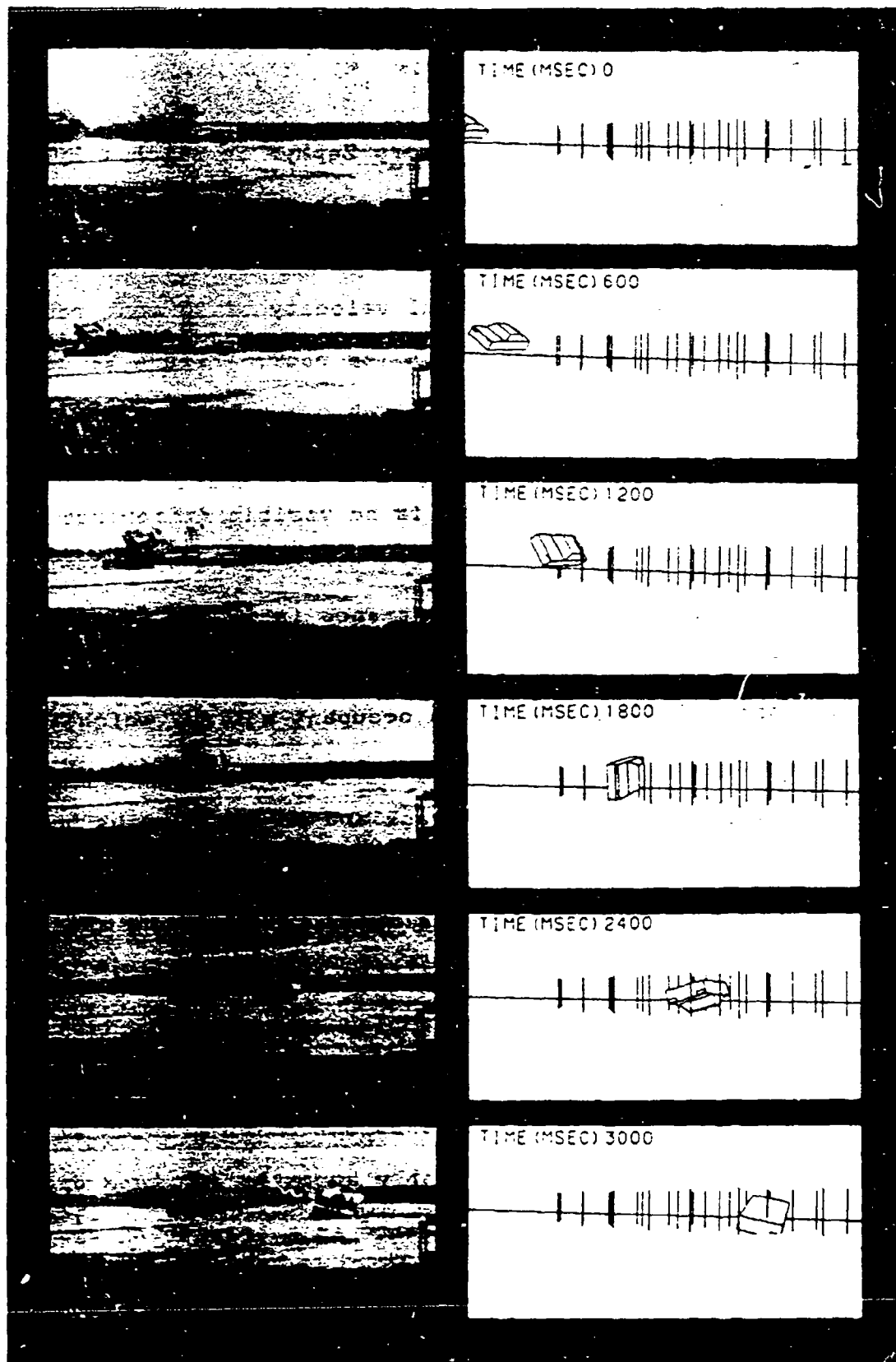


Figure 21 - Test No. 6, Zephyr
Test Film and Reconstructed Vehicle Motion

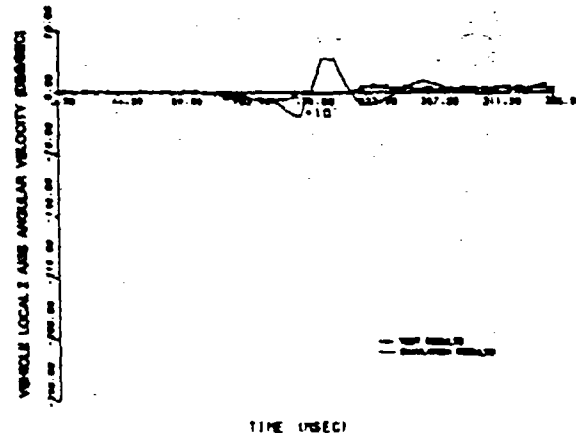
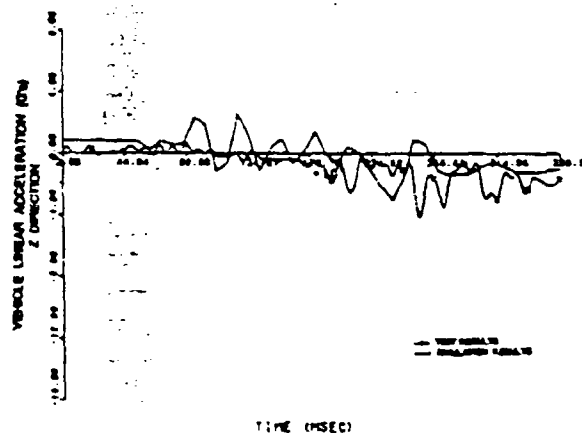
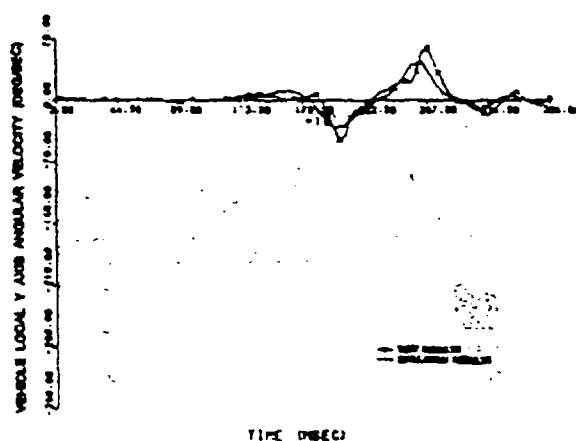
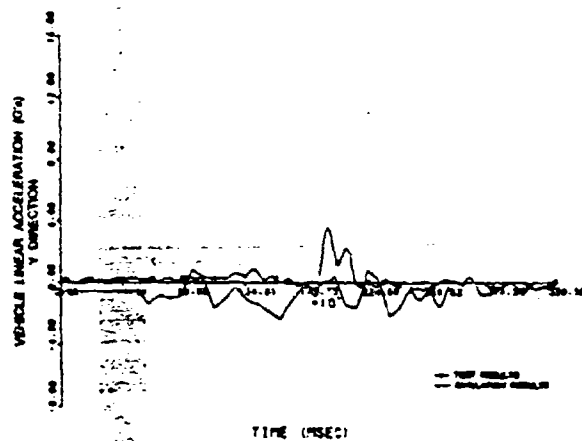
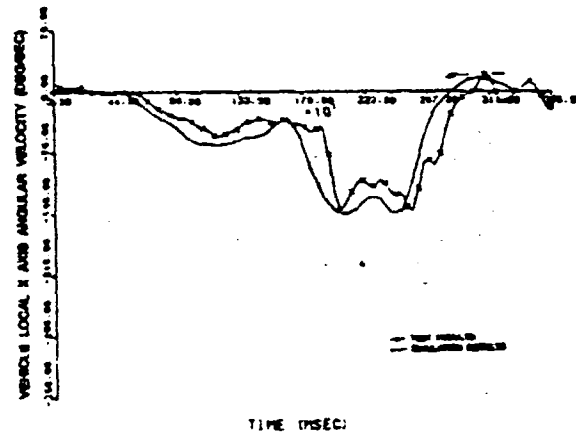
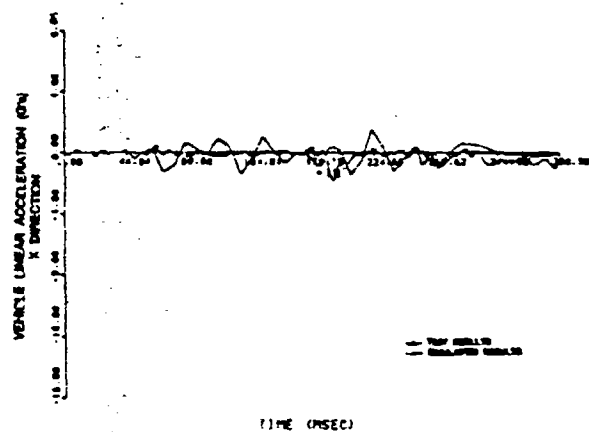


Figure 22 - Test No. 6, Zephyr
Vehicle Tri-axial Accelerometer and Angular Rate Gyro Data
From Test and Reconstructed Motion

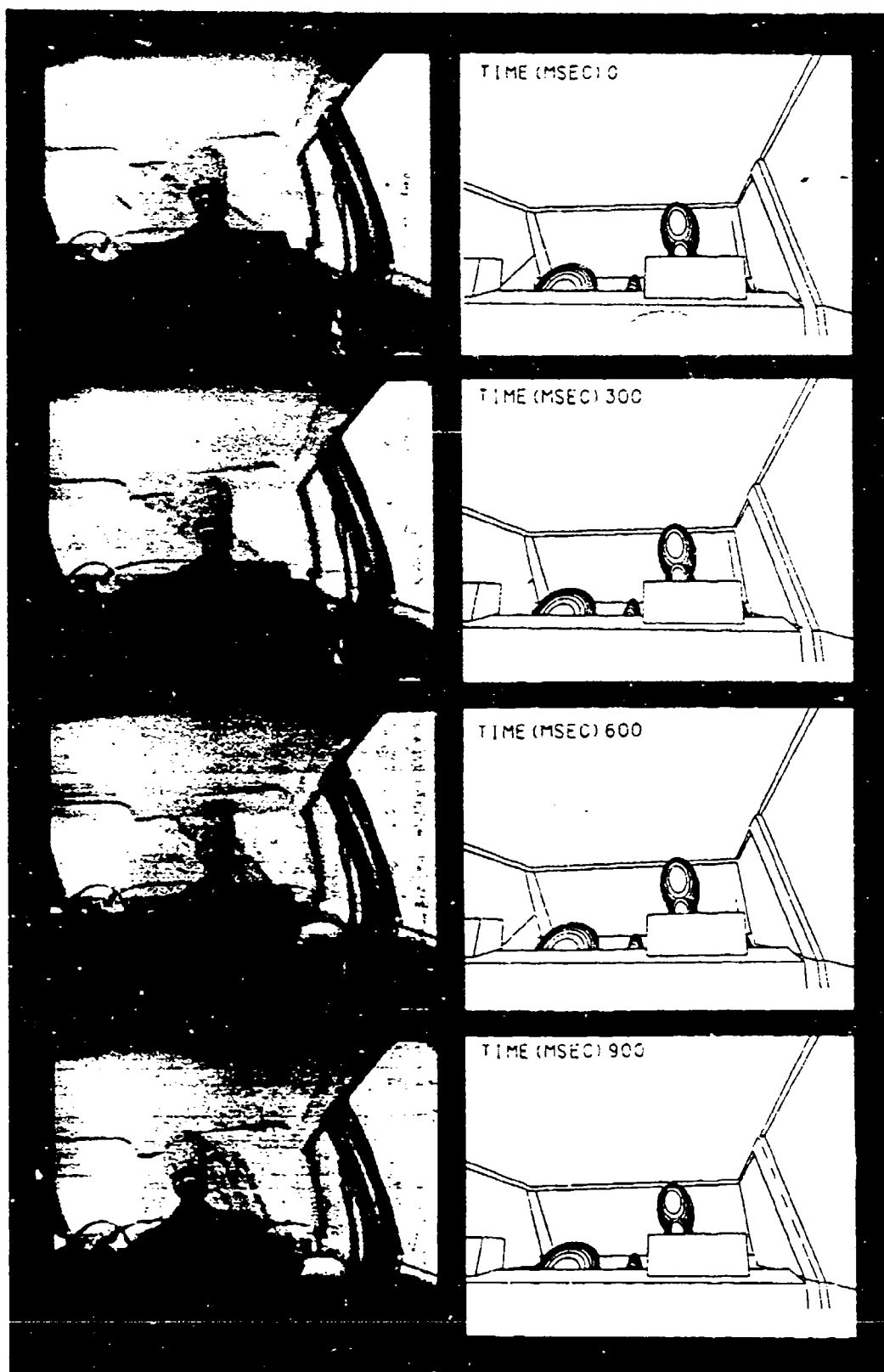


Figure 23 - Test No. 6, Zephyr
Test Film and Simulated Occupant Motion

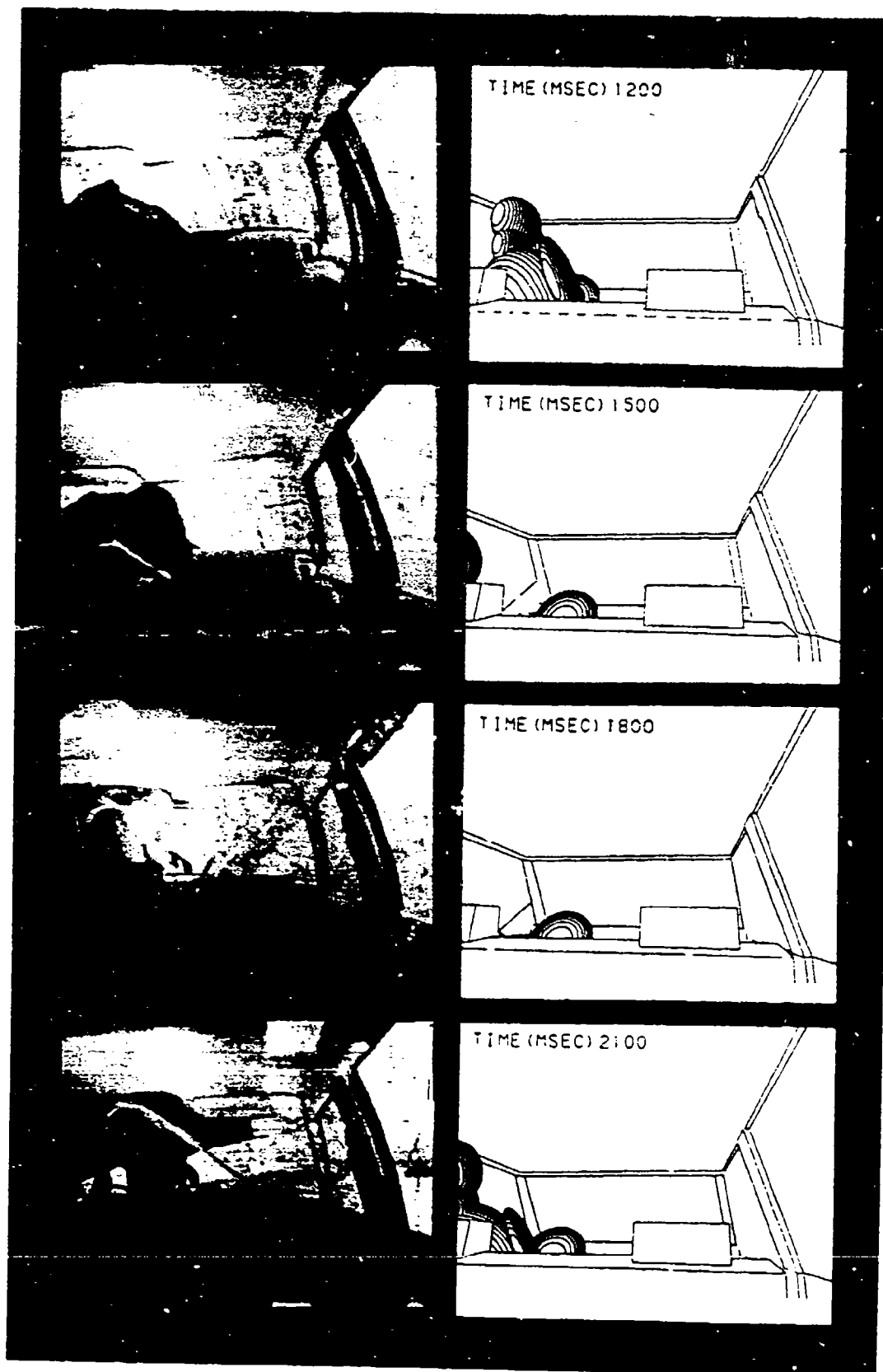
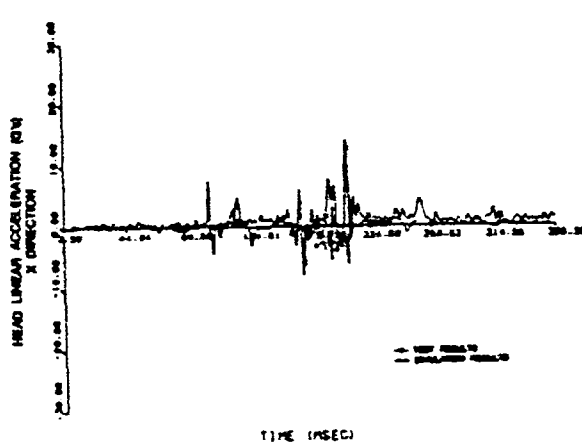
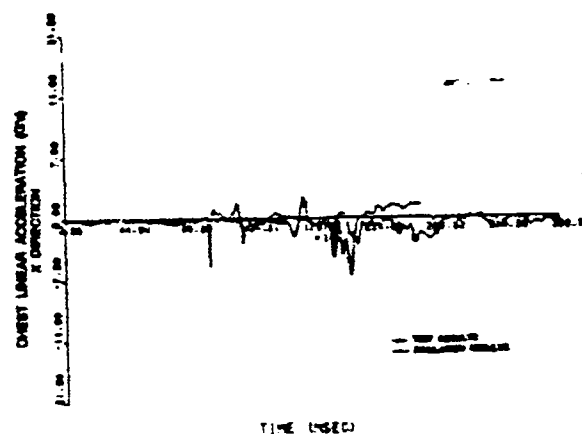


Figure 23 - continued

seen from the various viewing angles and, consequently, the reconstructed vehicle motion is probably incorrect. Figure 24 shows the dummy head and chest acceleration plots, and Figure 25 shows the neck load cell forces and torques. Again, they do not reveal much useful information.



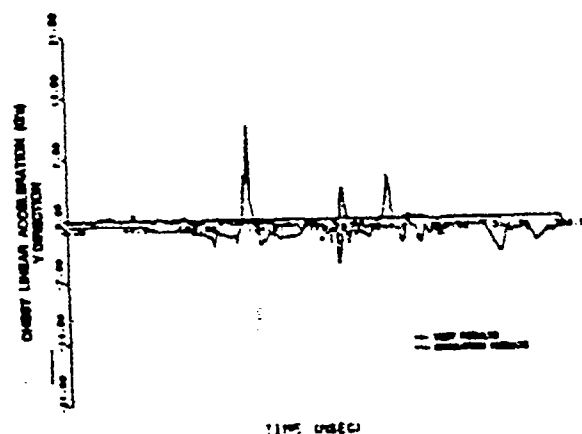
TIME (msec)



TIME (msec)



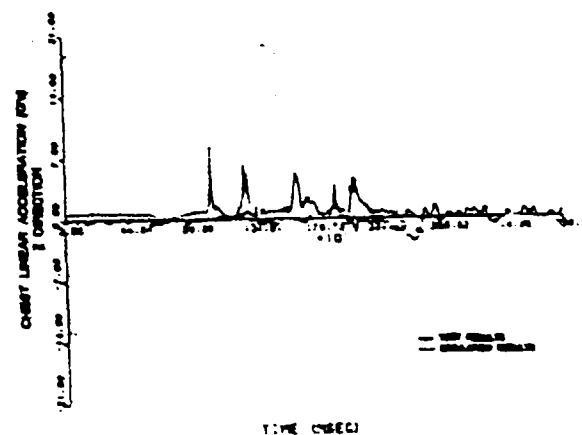
TIME (msec)



TIME (msec)



TIME (msec)



TIME (msec)

Figure 24 - Test No. 6, Zephyr
Head and Chest Tri-axial Accelerometer Data From The Test and
ATB Occupant Simulation

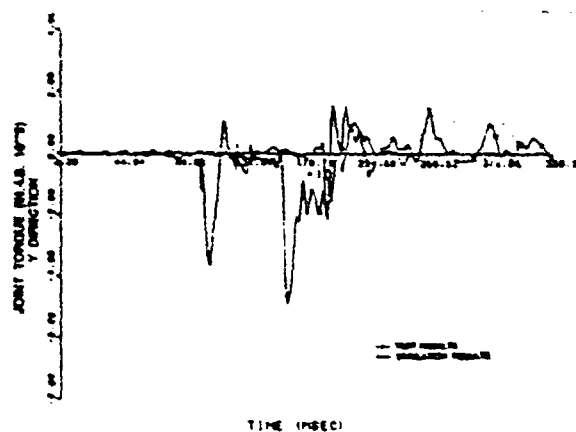
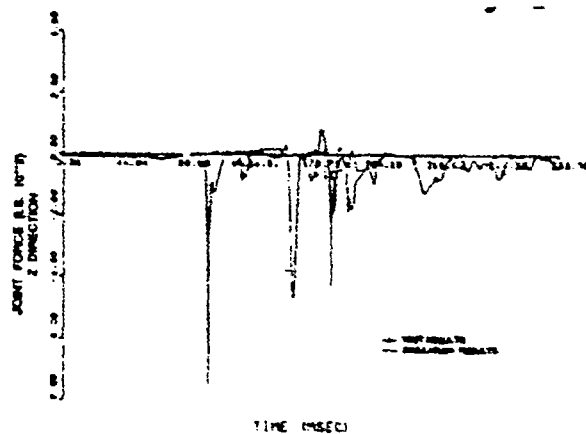


Figure 25 - Test No. 6, Zephyr
Neck Load Cell Data From Test and ATB Occupant Simulation

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