Performance of an Automatically Deployable ROPS on ASAE Tests

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Abstract

In the U.S., approximately 132 agricultural tractor overturn fatalities occur per year. The use of rollover protective structures (ROPS), along with seat belts, is the best–known method for preventing these fatalities. However, one impediment to ROPS use is low–clearance situations, such as orchards and animal confinement buildings. To address the need for ROPS that are easily adapted to low–clearance situations, the Division of Safety Research, National Institute for Occupational Safety and Health, developed a prototype automatically deploying, telescoping ROPS (AutoROPS). The NIOSH AutoROPS consists of two subsystems. The first is a retractable ROPS that is normally latched in its lowered position for day–to–day use. The second subsystem is a sensor that monitors the operating angle of the tractor. If an overturn condition is detected by the sensor, the retracted ROPS will deploy and lock in the full upright position before ground contact. Static load testing and field upset tests of the NIOSH AutoROPS have been conducted in accordance with SAE standard J2194. Additionally, timed trials of the AutoROPS deployment mechanism were completed. The results of these tests show that the NIOSH AutoROPS has significant potential to overcome the limitations of current ROPS designs for use in low clearance as well as unrestricted clearance operations.

Keywords. **Tractor safety, ROPS, Rollover, Overturn.**

Tractor overturns are the leading cause of fatalities in the agricultural industry. In the U.S., approximately 132 fatalities occur per year (Myers and Snyder, 1993). The use of rollover protective structures (ROPS), along with seat belts, is the best–known method for preventing these fatalities. ROPS use is increasing (Zwerling et al., 1997); however, the number of overturn–related fatalities per year has not been declining significantly (National Safety Council, 1997). Too many tractors still do not have a ROPS.

One impediment to ROPS use is low–clearance situations, such as orchards and animal confinement buildings. Many smaller tractors are now equipped with manually extending or foldable ROPS for use in such situations. However, these ROPS will only

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provide protection if the operator chooses to raise them. Available data do not indicate the number of injuries or fatalities due to the failure to raise adjustable ROPS. Between 10% and 20% of new tractors are reported to be operating without ROPS (Myers and Snyder, 1993). Some of these may be due to a need to operate these tractors in low–clearance situations.

To address the need for ROPS that are easily adapted to low–clearance situations, the Division of Safety Research, National Institute for Occupational Safety and Health, developed a prototype automatically deploying, telescoping ROPS (AutoROPS). Technology innovations of this type have recently been developed for protecting drivers and passengers from the overturn hazard on convertible automobiles (Mowry, 1999; Mercedes–Benz AG, 1995; U.S. Department of Transportation, 1989). The NIOSH AutoROPS is a passive device consisting of a retractable ROPS that is normally latched in its lowered position for day–to–day use, and a sensor that monitors the operating angle of the tractor. If an overturn condition is detected by the sensor, the retracted ROPS deploys and locks in the full upright position before the overturning tractor contacts the ground. Static load testing and field upset tests of the NIOSH AutoROPS have been conducted in accordance with SAE J2194. Additionally, timed trials of the AutoROPS deployment mechanism were completed. This paper discusses the design of the NIOSH AutoROPS as well as the results of the different testing phases.

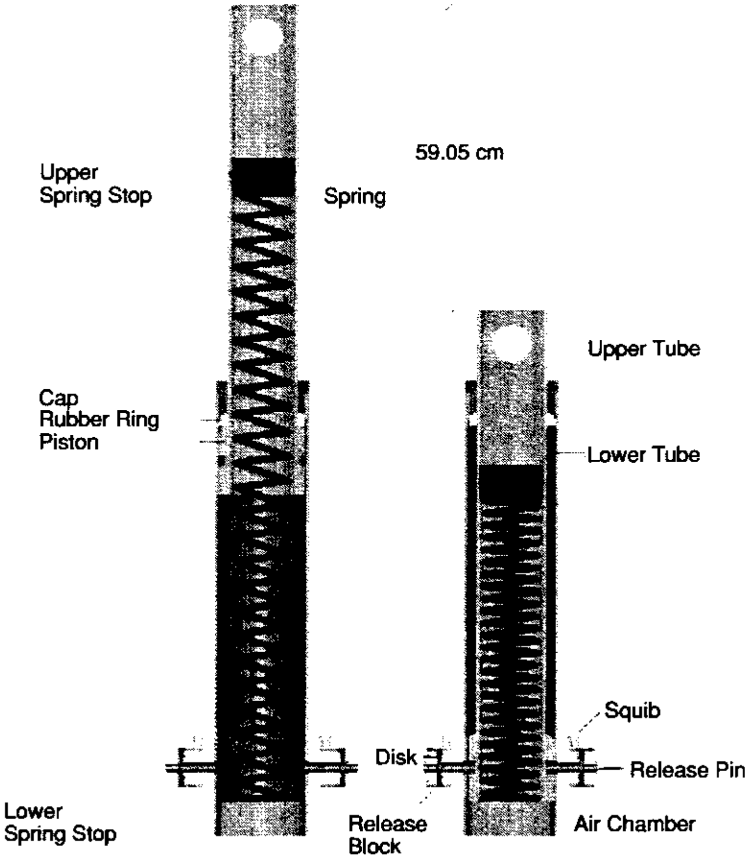
AutoROPS Subsystem

Spring–Action Telescoping Structure

The AutoROPS structure consists of a telescoping tubular section that is extended to its full dimensions by a spring (fig. 1). An initial retracted height for the AutoROPS was established based upon the sitting midshoulder height for a 5th percentile female (NASA, 1978). This is intended to keep the AutoROPS below head height for nearly all drivers so that nearly all drivers can see any implement over the crossbar. The required deployment distance of 59.05 cm (23.25 in.) was determined by keeping the deployed height of the AutoROPS crossbar approximately equal to the height of a commercial ROPS. A key design parameter was that the deployment distance must be traveled in less than 0.3 s. This criterion was based on Baumann and Wunsche's (1990) report that a deployment time of 0.3 s or less is adequate to protect convertible automobile occupants from an overturn hazard. This is well below the 0.75 s that Hathaway and Kuhar (1994) indicate that it takes for a tractor in a rear overturn to go from a point–of–no–return to ground–contact. The telescoping structural section is made from a plain carbon steel seamless tube. The main compression spring is made from 12 mm (0.47 in.) diameter stainless steel wire and has a 4.4 N/mm (25 lb/in.) modulus. Component sizing of the two–post telescoping structure was facilitated by use of finite element analysis (FEA) and computer–aided design (CAD) software (Harris et al., 1997; Harris et al., 1998).

Release Mechanism

Pyrotechnic squibs provide the force needed to simultaneously disengage two release pins that hold each post of the structure in the retracted configuration (fig. 1b). A 1.2 amp, two millisecond duration current ignites an initial 550 kPa (80 psi)/10 cc pyrotechnic gas expansion. Each release pin is attached to a disk that is forced outward by the gas pressure acting in an expansion chamber.



(a) deployed **(b) retracted**

Figure 1. AutoROPS structure and mechanism.

Latch–up Mechanism

Two spring–loaded (8.8 N/mm (50 lb/in.)) pins on either side of each base post snap into place underneath the upper post to lock the AutoROPS into the deployed position (fig. 1a). These latch pins support the structure, especially for loading in–line with the posts. A rubber ring was designed and bonded to the underside of the cap of the outer tube to absorb the energy of the piston impact during deployment (Howard, 1998).

Retract Cylinder

The AutoROPS is retracted by a 28.58 mm (1.125 in.) bore by 610 mm (24 in.) stroke hydraulic cylinder inside of the spring. The cylinder is base–mounted to a manifold block. Ports in the mounting block direct hydraulic fluid to ports at both ends of the retract cylinder. A two–position, manually–levered valve currently controls the hydraulic flow for raising and lowering the upper structure. For this prototype design, the cylinder is connected to the telescoping portion of the AutoROPS by threaded pins, inserted manually through openings at the top of each upright.

Sensor Subsystem

The design goal of the AutoROPS sensor was to design a device that 1) did not rely on the tractor's center of gravity, 2) was able to reliably predict an overturn condition, and 3) provided a signal that would deploy the retracted AutoROPS before the tractor contacted the ground. Figure 2 shows a block diagram of the AutoROPS sensor. As can be seen from this diagram, the sensor consists of three accelerometer circuits, a multiplexer, a microcontroller, and a triggering circuit. The accelerometer circuits are configured to monitor the roll and pitch of the tractor. The accelerometer signals are passed to the microcontroller via the multiplexer. The microcontroller contains an algorithm that monitors the received signals and determines whether or not the tractor is operating in a safe condition. If an overturn condition is sensed, the microcontroller will send a signal to the triggering circuit to deploy the telescoping AutoROPS.

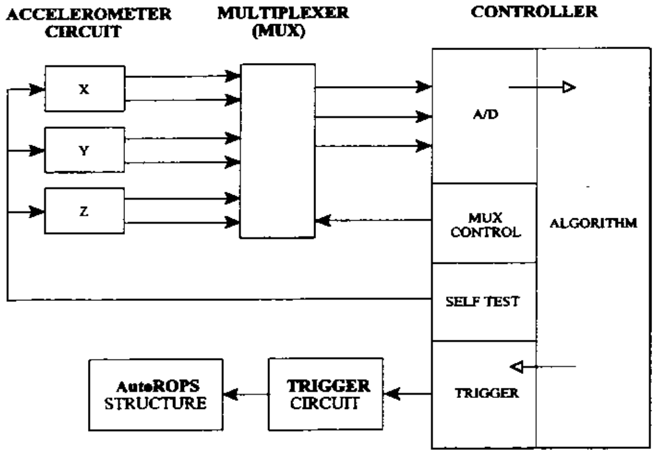


Figure 2. AutoROPS sensor block diagram.

Accelerometer Circuits

The accelerometers used are ADXL05 accelerometers manufactured by Analog Devices. The accelerometers are configured so that they are DC coupled. Configured this way, the accelerometers will sense static accelerations such as the Earth's gravity and use this constant force as a position reference from which inclination angles can be derived (Analog Devices Data Sheet, 1996). The angles are calculated by the formula:

$$\text{Angle} = \arcsin\left[(V_{out} - 2.5)/2.0\right] \tag{1}$$

The X–axis and Y–axis accelerometers are mounted perpendicular to the force of gravity and 90° to each other to sense pitch and roll angles, respectively. The Z–axis accelerometer is mounted parallel to the force of gravity so that it senses both pitch and roll angles. Each accelerometer can be placed into a self–test mode to ensure it is operating properly. The circuits also incorporate passive low–pass filters to eliminate both electrical and mechanical tractor noise. Each accelerometer sends two signals to the multiplexer, one for the self test mode and one for normal operating mode. The accelerometers are embedded inside crystal ovens manufactured by Isotemp Research, Inc. These ovens regulate the operating temperature of the accelerometers to eliminate drift caused by temperature changes.

Multiplexer Circuit

The multiplexer, a Motorola MC74HC4053, controls which accelerometer signals (self–test mode or normal mode) the microcontroller receives. When the sensor is turned on, the microcontroller configures the multiplexer so that it receives the self–test mode signals. After the self–test completes, the multiplexer is switched so that it sends the normal mode signals to the microcontroller.

Microcontroller Circuit

The microcontroller used is a Microchip PIC16C71. The microcontroller contains the program that controls the operation of the accelerometers (self–test mode or normal mode), the operation of the multiplexer, and the algorithm for determining when an overturn is imminent. The microcontroller receives all three accelerometer signals from the multiplexer simultaneously. However, the operations performed on these signals are done sequentially. Each signal is switched to the on–board A/D convertor sequentially and read. Each digitized value is then stored in memory and used by the algorithm later. At startup, the microcontroller places all three accelerometers into self–test mode and switches the multiplexer so that the self–test mode signals are being read. Upon completion of the self–test, the controller switches the accelerometers into normal mode and switches the multiplexer so that the normal mode signals are being read. At the completion of the self–test, the microcontroller is put into a continuous loop of reading the three accelerometer signals, processing these signals, and determining whether or not an overturn is imminent. If an overturn is detected, the controller will send a signal to the triggering circuit. Otherwise, the loop is continued and new readings are taken.

Trigger Circuit

The triggering circuit consists of a National Semiconductor LM1950 line driver and a Potter & Brumfield RTD14012 relay. The line driver receives the overturn trigger signal from the microcontroller and drives the relay. The normally open contacts of the relay are connected to pyrotechnic squibs that, when ignited, deploy the telescoping AutoROPS.

Tests

Release Mechanism Tests

The release mechanism tests were completed by securing the AutoROPS structure to a test bed. One pyrotechnic squib was used. An OptoTrak 3020 optical motion measurement system, sampling at 200 Hz, was used to record the position of the structure as it deployed. Two markers were placed on one side of the AutoROPS: one on the top of the fixed post and the other on top of the sliding post. A timing circuit connected to a switch was used to activate the squib. Video cameras were used to capture the event. The OptoTrak data were used to calculate deployment time.

SAE J2194 Static Load Tests

All static loading tests, with the exception of the vertical crush test, were run via a QuickBASIC program and PC link to an MTS MicroProfiler under displacement control. As required in the SAE standard, the energy of the force versus the deflection curve was continually monitored by the program. Loading was provided by 20 ksi hydraulic actuators. The vertical crush test was performed under manual displacement control to the required load level.

SAE J2194 Field Upset Tests

To meet the field test requirements of SAE J2194, engineers and technicians at the NIOSH Pittsburgh Research Laboratory (PRL) modified a Ford 4600 tractor with remote control capability. In addition, a rear and side overturn test ramp was constructed to the specifications set forth in SAE J2194.

The AutoROPS was mounted on the axle housing of the tractor, as a commercial ROPS would be attached. The sensor was mounted near the center of the tractor and aligned so that the X–axis was front–to–back, the Y–axis was side–to–side, and the Z–axis was up–and–down.

The tractor was equipped with a Fieldworks F7500 ruggedized laptop. The laptop contained a National Instruments DAQCard–700 and LabVIEW software. The DAQCard–700 was configured to accept five differential analog inputs. A LabVIEW program was written to record the data to the laptop's hard disk. The five channels of data collected were X–axis, Y–axis, Z–axis, Vcc, and Trigger Signal. The data were recorded at a sampling rate of 250 Hz and saved as a tab–delimited text file. In addition, numerous video cameras were set up to record the overturn tests from different angles.

The rear and side upset tests were conducted by first taking cone penetrometer readings in the impact area, in accordance with ASAE S313 (ASAE Standards, 1992), to ensure that the soil met or exceeded the soil firmness requirements of the standard. The tractor was aligned with the ramp, placed in the appropriate gear, and shut off. Following installation of the pyrotechnic squibs, the LabVIEW data collection program was started and the tractor engine re–started. For the rest of the test, the tractor operator set the governor setting, engaged the clutch, and performed steering necessary to keep the tractor on track to the overturn ramp through remote control. Once the overturn was achieved, the tractor engine was shut off and the tractor was returned to its wheels with a crane. When the test area was safe to enter, the LabVIEW program was stopped and the data were secured.

Results and Discussion

Release Mechanism Tests

The release mechanism for the AutoROPS was tested in the laboratory during early December 1998. Four tests were conducted. In these lab tests, the two–post structure consistently deployed in less than 0.3s and latched–up securely. In late December, 1998, the AutoROPS was latched in its lowered position indoors for approximately 2.5

months. In early March, 1999, the AutoROPS was deployed. This test also produced a deployment time of less than 0.3s.

SAE J2194 Static Load Tests

The AutoROPS structure was tested to the SAE J2194 static load test sequence during July 1999. The first longitudinal and transverse tests were terminated (test load successfully sustained) when they reached load levels equal to those recorded by NIOSH (Etherton and Harris, 1995) for standard ROPS for the same tractor. These load levels were achieved before the energy criterion of the standard was met. The second longitudinal load was terminated when it met the energy criterion of the standard and before it reached a load level found for standard ROPS. No permanent, or plastic, deformation was observed as a result of any of the four tests of the sequence.

SAE J2194 Field Upset Tests

Figure 3 shows the data collected during a rear upset test. For this test, the tractor was put into 3rd gear with an engine speed of 2200 RPM, producing a tractor speed of approximately 5.6 km/h (3.5 mph). Cone penetrometer readings were taken at six locations in the impact area. The average cone index of these six locations was 2814 kPa. Figures 4 and 5 show the position of the tractor just prior to climbing the ramp and at the completion of the roll, respectively. It can be seen from figure 3 that the X–axis and Z–axis signals increased as the tractor climbed the ramp. The AutoROPS deployed when the tractor reached an angle of approximately 65° (Z–axis). Video footage was used to determine the time after the AutoROPS deployed until ground contact was made. The time calculated was approximately 2.0 s.

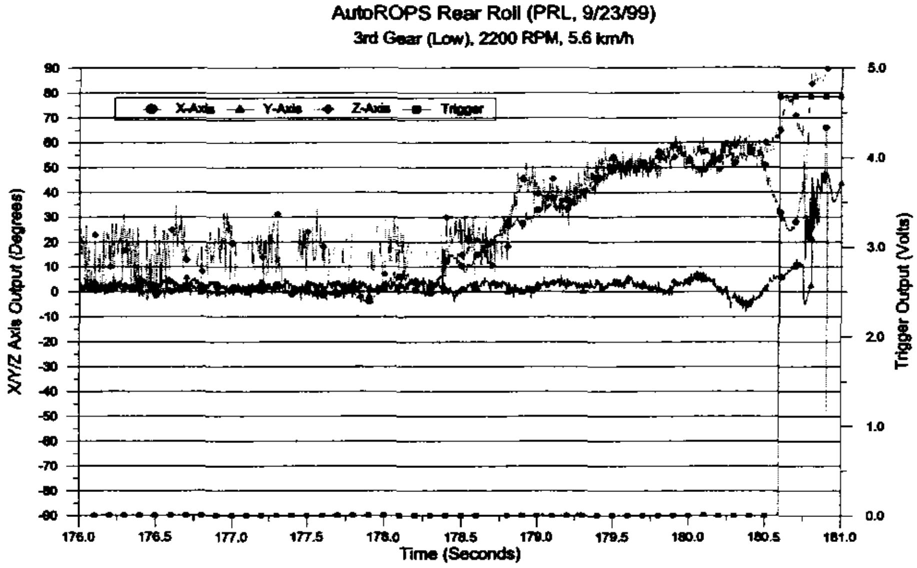


Figure 3. Accelerometer outputs and trigger signal during rear roll.

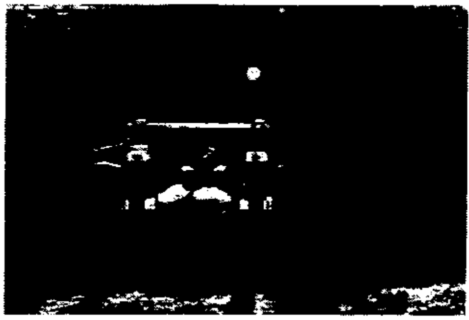


Figure 4. Rear roll approach.

Figure 5. Rear roll finish.

Figure 6 shows the data collected during a side upset test. For this test, the tractor was put into 6th gear with an engine speed of 2000 RPM, producing a tractor speed of approximately 10.5 km/h (6.5 mph). Cone penetrometer readings were recorded in nine different locations in the impact area. The average cone index for these nine locations was 2699 kPa. Figures 7 and 8 show the position of the tractor just prior to entering the side overturn pit and at the completion of the roll, respectively. It can be seen from figure 6 that, as the tractor entered the overturn pit, the Y–axis signal decreased while the Z–axis signal increased (starting at approximately 89.25 s). The AutoROPS deployed when the tractor reached an angle of approximately 60° (Z–axis). Video footage was used to determine the time after the AutoROPS deployed until ground contact was made. The time calculated was approximately 1.5 s. A change in the X–axis signal (at approximately 89.5 s) can also be seen. This was caused by the impact of the right tractor wheel with the ramp.

It should be noted that the speed of the tractor mentioned above is less than the required minimum speed of 16 km/h as specified in SAE J2194. Side upsets tests were also conducted with the tractor traveling at approximately 16.1 km/h. At this speed, the impact of the right wheel with the ramp was so severe that the X–axis accelerometer produced a sharp spike, which the AutoROPS sensor interpreted as an overturn, thus deploying the structure before significant chassis roll had occurred. The sensor was also evaluated by operating the tractor over rough terrain at a variety of forward speeds. No false deployments of the AutoROPS occurred during these tests. The possibility of deployments when the tractor is not overturning may exist. ROPS are typically installed at a layback angle away from the operator's seat. This should provide adequate distance between the operator and the AutoROPS should it deploy at an unintended time. This will be investigated further in future research.

Conclusions

An automatically deploying, telescoping ROPS has been developed that would normally be stored in a compact form, allowing for use in low–clearance situations, but expanding automatically to its full dimensions to protect the operator should an overturn occur. A sensor has also been developed that monitors the operating angle of the tractor and determines if an overturn is imminent. Results from actual field upset

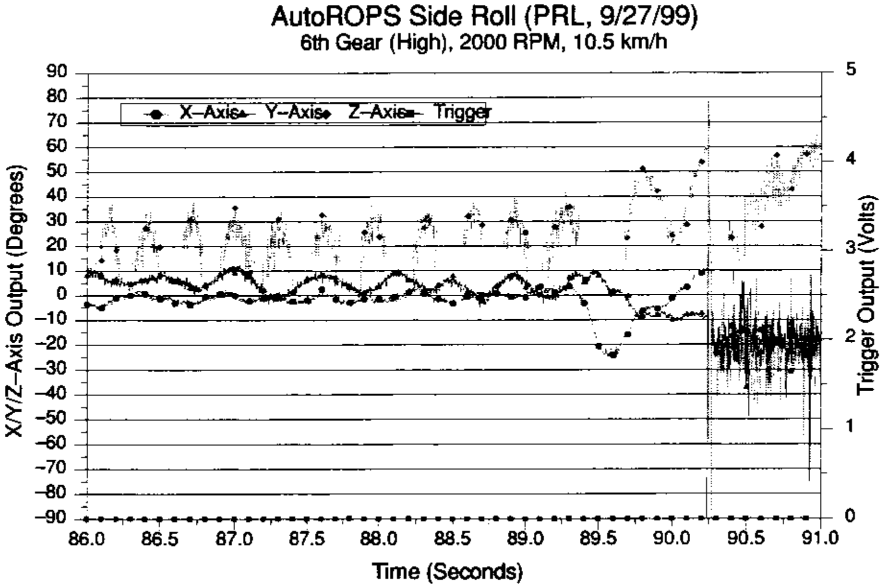


Figure 6. Accelerometer outputs and trigger signal during side roll.

Figure 7. Side roll approach.

Figure 8. Side roll finish.

conducted in accordance with SAE J2194 show that the AutoROPS structure absorbed the impact with no measurable permanent deflections in the structure. The sensor was able to predict the overturn in a timely manner so that the AutoROPS was fully deployed and locked before ground impact occurred.

The primary goal of this phase of the research was to build a structure that would prove that an automatic ROPS can be built that will reliably deploy on signal, rise in a sufficiently short time, firmly latch in its deployed position, and satisfy the SAE J2194 testing requirements. Only limited effort was made in the initial studies to build a structure that optimized the design for ease of use and lower cost. For example, the steel tubing selected for this prototype structure was a commonly stocked diameter and wall thickness. These conveniently chosen dimensions proved satisfactory in the FEA models that were run prior to conducting the static load tests. This material was also shown in the laboratory tests mentioned in this article to provide the required protective envelope for the operator and to experience very little deformation under the required test loads.

The release and latching mechanisms are functionally reliable, but they may need to be redesigned so that they interfere less with the normal tractor work that takes place near them. The material cost needs to be reduced, and a method must be developed to easily reset the AutoROPS should a false deployment occur in a non–overturn situation. These improvements are currently being developed by NIOSH staff. Sensor refinements are also currently underway to eliminate false and premature deployments. Continued research will also need to consider environmental corrosion effects and the adequacy of the protective envelope. Ways to improve the rate of seatbelt usage also need to be developed since increasing seatbelt usage is a "coupled" factor in any ROPS system effectiveness.

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