Smart head restraint system

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Abstract: This paper reports the design and development of a novel head restraint system for automotive applications to reduce whiplash injuries to occupants. This head restraint mechanism is combined with a pair of ultrasonic sensors, actuators and control algorithm to form an active head restraint system, which detects the position of an occupant’s head when seated in the car and moves the head restraint into an optimum position to reduce the chances of receiving whiplash injuries in the event of a rear impact. The system monitors significant changes in the position of the head and moves the head restraint to the desired position. A system demonstrator is built and successfully tested.

Key words: Head restraint, whiplash, smart/intelligent head restraint, occupant protection, rear impact.

INTRODUCTION

Whiplash is an injury of the cervical spine soft tissue, caused by the sudden acceleration of the head relative to the torso, which occurs during a rear-end collision, mostly occurring at low impact velocities, typically less than 20 km/h [1, 2]. Injury statistics indicate that almost every fourth injury to car occupants is related to rear-end crashes, with three quarters of these injuries being in the neck. Although officially classed as a minor injury, whiplash can lead to long, painful and debilitating symptoms for many years following a crash. Whiplash injuries typically cost the British insurers over £1 billion annually and account for over 80% of the total cost of personal injury claims [3]. It has been estimated that the direct cost of whiplash injuries in the USA is approximately $4.5 billion annually. This cost shows an increasing trend and reflects the insurance premiums paid by the motorists. There are further unaccounted medical costs and the cost of lost working days to the economy because of whiplash injuries. Moreover, the reduction in the quality of life of the whiplash sufferers is difficult to quantify.

The primary method of preventing whiplash-induced injury in motor vehicles is the use of a head restraint. A well designed and correctly aligned head restraint will vastly reduce the risk of injury to the head, spine and neck during rear-end collisions [4]. Head restraint geometry, specifically head restraint height and horizontal distance ‘setback’ of the head restraint from the occupant’s head can have a significant influence on the likelihood and severity of a whiplash injury in rear impact collisions. Recent research by Thatcham indicated that 72% of front seat occupants failed to adjust their head restraints correctly or had head restraints that were incapable of offering any protection [3]. The Insurance Institute for Highway Safety in the USA published similar results [4]. Thatcham’s research suggests that the car occupants do not take adjusting head restraints seriously and therefore there is a need for a solution to alleviate the problem of whiplash injuries caused by rear-end automotive crashes. Whiplash can be prevented with a correctly positioned good head restraint system. To be effective, a head restraint must be as close to the back of the head as possible (touching is best) and the top of the restraint should be as high as the top of the head. An active head restraint mechanism that would adjust itself to the correct position would potentially be a solution towards solving the problem. The head restraint would always be in the correct position to reduce the chance of receiving whiplash injuries in the event of a rear impact.

This paper reports the design and development of a concept for a smart head restraint system that adjusts itself automatically to the correct position in order to reduce the amount of whiplash injuries suffered by millions of people all over the world.

CURRENT WHIPLASH REDUCTION SOLUTIONS

Industrial ‘anti-whiplash’ products

Most head restraints are either of a fixed type or manually adjustable in the vertical direction for height setting. Some also have a tilt mechanism to allow limited
setback adjustments. In recent years, a number of novel ‘anti-whiplash’ head restraint designs have been suggested and implemented. Some notable ones are mentioned here.

The self-aligning head restraint (SAHR) system has been in production since 1997. During a rear-end impact, the head restraint moves upward and forward via a mechanical linkage, supporting the head before the relative motion of the head and torso becomes significant. The system is activated by the force of the occupant’s body pressing the seat backrest during a rear impact. When the load of the occupant decreases, the mechanism returns the head restraint to its original position. No replacement of the seat is required after an accident since it resets itself. Saab’s SAHR was found to be effective in reducing whiplash injuries [5]. Similar designs were also adopted by a number of other companies.

Autoliv developed the Whiplash Protection System (WHIPS) for Volvo that has proven to be effective in rear-end impacts. Initially, a pair of four-bar linkages on both sides of the seat that hinge the backrest to the seat pan allow the seatback to move backwards, thus allowing the torso to move together with the head, reducing relative displacement. Then a plastically deformable element allows tilting of the seatback rearwards to allow further energy absorption, which needs to be replaced after a rear-end collision [6, 7].

The Toyota Whiplash Injury Lessening (WIL) system aims to reduce the relative motion between occupant’s head and torso [8]. This is achieved by seatback and cushion design that yields in a controlled manner during a rear impact to reduce the whiplash effect. The WIL seat was included as a standard component for 2000 Toyota Avalon, Celica and Echo [9].

Mercedes Benz have recently introduced an active head restraint, using an on-board crash sensor that activates a linkage in the head restraint which pushes it forward and upward to close the gap between the occupant’s head and head restraint [3].

Whiplash protection for the aftermarket

The Autoliv Anti-Whiplash System (AWS) for the aftermarket for front-seat occupants consists of a metal sheet with tear grooves that is installed between the seat rails and the seat. When the vehicle is hit from behind, the tear grooves absorb the impact by gradually ripping apart. The seat then pivots rearwards in a controlled manner instead of violently pushing the occupant’s shoulders and lower neck forward [10].

WipGARD, also developed by Autoliv, is a yielding device that could be fitted to the existing seat rail, which allows the seat to move back horizontally and rotate to the rear. WipGARD reduces the severity of the S-curve and decreases the rebound speed at which the body will be thrown forward [11]. It is also designed to give protection to smaller, lighter occupants such as women.

Further ‘anti-whiplash’ concepts

In 1999, Autoliv launched the Self Inflating Head Restraint (SIHR), an anti-whiplash system specially developed for rear-seat occupants. During rear impact, air is pressurized from a large bag in the backrest to a small bag in the head restraint, which then moves forward to reduce, or eliminate, gaps between the occupant’s head and the head restraint [12].

An airbag-based inflatable system that operates on a similar mechanical principle to that developed by Autoliv was reported [13]. The difference was that the airbag is inflated around the neck supporting it, instead of extending outwards by the pressure the head exerts on the headrest itself.

An inflatable head restraint, with an integrated airbag into the foam, was also reported [14]. It would enlarge sufficiently in all directions to protect occupants of all sizes independently from the pre-adjusted position.

A whiplash protection device in the form of a collapsing spring consisting of two shallow angled cone tubes on a double-ended conical mandrel was suggested [15]. One of the tubes is attached to the seat and the other to the floor. During rear impact the conical tubes are pushed onto the mandrel and deform elastically allowing a translational motion of the seat and locking the tubes preventing springing back.

A damping seat slide system was developed which reduces the acceleration of the occupant, thus reducing the relative motion between the head and torso, which in turn reduces the whiplash effect [16]. The seat slide was mounted between the seat base and the car floor, allowing a damped translational motion of the seat backwards. The damping mechanism is triggered by a sensor.

SENSOR APPLICATIONS IN OCCUPANT DETECTION

The primary application of sensor systems in passenger cars is generally for occupant detection in conjunction with airbag deployment. Stereovision systems provide information about the occupant presence and location within the vehicle to improve the control of the airbag firing [17]. Autoliv also have an occupant detection and classification system ready for production which uses an arrangement of five ultrasonic sensors in combination with a weight sensor integrated into the seat, a seat position sensor and a sensor in the buckle to determine the size and sitting position of the seat occupant [18]. Various other sensing technologies have been tested for similar applications but are not expected to reach production within the next five years. These include: infrared displacement [19], thermal imaging [20] and omni-directional cameras [21].

Sensor-based systems have not yet been used in head restraint applications. Massara [22] reports experiments using ultrasonic sensors mounted on top of a head restraint. He successfully used this arrangement to detect
the presence and seated height of occupants with a range
of hairstyles and sitting positions. He concluded that ul-
trasonic technology provides a cost-effective, high perfor-
mance solution and that a sensor-based active head restraint
was feasible. He did not however build a full prototype; nei-
ther did he use the ultrasonic sensors to detect the backset.

SMART HEAD RESTRAINT DESIGN

The mechanical design concept

None of the so-called active head restraints currently on
the market are ‘active’ in the sense that they only move into
position once an impact has occurred. The truly active head
restraint mechanism proposed in this paper will move the
head restraint into an optimum position and continuously
monitor the changes in the position of the head and make
adjustments, and be always in a state of readiness for an
impact to occur. The major benefit of this system is the fact
that it will take over the responsibility of adjusting the head
restraint from the occupant and the restraint will always be
in the optimum position before the impact takes place.

The system consists of mechanical horizontal and verti-
cal adjustment mechanisms with actuators, sensors to
detect and monitor the position of the occupant’s head, and
control software that continuously adjusts the position of
the head restraint.

The horizontal and vertical movements of the head re-
straint are controlled by two separate DC motors placed in
the backrest of the seat.

Setback mechanism (the horizontal motion)

Figure 1(a) shows the details of the design for the setback
mechanism which enables the horizontal motion of the
headrest. In normal operation the tension in the motor
cable keeps the setback wheel in the down position (Figure
1(b)). When the setback wheel is in the down position the
second cable is taut and the sprung loaded locking pins
are not engaged with the setback shafts. This means the
mechanism can move back and forth freely in the horizontal
plane.

In the event of a rear impact the occupant’s head hits
the head restraint. As soon as the head restraint begins
to move rearwards the motor cable becomes slack. The
setback springs are then compressed and absorb the kinetic
energy from the head. Once the cable is slack, the sprung
loaded locking pins are able to move outwards pulling the
setback wheel upwards (Figure 1(c)) and act like a ratchet
mechanism preventing the setback springs forcing the head
restraint forward. The system is reset when the tension in
the cable provided by the motor becomes great enough to
pull the setback wheel downwards again, disengaging the
locking pins allowing free movement once more.
M Acar, S J Clark and R Crouch

Figure 2 The proof of the concept mechanical system design assembly.

Figure 3 Sensor performance after calibration.

The main advantage of this design is that the springs are able to absorb the energy from a rear impact in a controlled manner, without releasing that energy back onto the occupant’s head.

Height adjustment (the vertical motion mechanism)

The vertical system is designed such that the restraint cannot accidentally be pushed in by passengers sitting at the rear of the car by pulling it down. The horizontal system also has a spring mechanism that absorbs energy during the impact. Hence, the vertical mechanism has been designed by using a 40:1 ratio worm and wheel. The vertical mechanism will be mounted in the seat back as low as possible to keep the centre of gravity of the whole mechanism as low as possible. The system resets itself and is therefore reusable unless permanent damage to the system occurs during a severe impact.

Figure 2 shows the complete assembly of the CAD model for the proof of concept mechanical system.

Sensor system development

Several sensor types have been investigated and infrared and ultrasonic sensors have been identified as having sufficient potential for detection of the occupant’s head position. By testing a sample of each sensor it would be possible to discover which is more appropriate for a smart head restraint system.

Daventech SRF04 ultrasonic range finder and Sharp GP2D12 infrared sensor were chosen for further investigation. Calibration tests showed that both sensors were reasonably accurate in detecting distance as shown in Figure 3. Readings were taken from the sensors at 5 cm intervals from 10 cm to 60 cm. The tests were conducted in normal daylight with no known other specific sources of interference existing.

The sensors ability to operate in a variety of conditions was tested in order to simulate the vehicle cabin environment. The first stage of testing was to see how the sensors respond to different hair types. Four volunteers, each with a different hair type, namely black, blonde and red hair and a bald head were tested. Readings were taken from the sensors at the same test conditions used during calibration. Ultrasonic sensors were least affected as shown in Figure 4 by different hair types.

Common sources of interference such as bright light, darkness, loud music and a mobile phone were also tested. It is clear from the test results that the effect of the interference sources is far less than the effect of the hair types.
The ultrasonic sensor performed very well on all the interference tests. The ultrasonic sensor, therefore, has been selected for the prototype development.

The compact size of the sensor allows a variety of attachment locations within the vehicle to be considered. The sensor must not be at any great risk from accidental damage and it must not pose any threat of injury to any vehicle occupant during normal operation or a crash situation. The location of the sensor must also allow it to determine the position of the occupant’s head over a wide range to ensure moderate amounts of seat occupant movement can be detected. Various alternatives include roof lining and A and B pillars of the car. However the head restraint is identified as the most suitable position for the sensors, since the position of the head relative to the head restraint can be determined directly. In addition there is sufficient space to conceal the sensor and there will be no distraction to the seat occupant as the sensor will be out of their line of sight. One further major benefit of this location is that a single sensor can detect both the distance and backset position of the head by moving the head restraint up and down to scan the area in which the seat occupant’s head would be.

A dual sensor system as shown in Figure 6 has the benefit of increased area over which the head is detectable. This would allow for a larger amount of OOP movement by the seat occupant before their head moved out of detectable range. Precisely how much extra area is gained with a dual sensor arrangement is hard to quantify without mapping out the detectable zone, but from inspection the dual sensor arrangement is clearly superior. There is also some reliability benefit: if one sensor should fail the other will provide some degree of operational ability until the system can be fixed. Due to these factors a dual sensor arrangement will be developed for the demonstrator model.

**Integration and testing of the systems**

Control software has been written and implemented to enable continuous measurements of the position of the occupant’s head and adjustment of the head restraint to a position for reduced whiplash injury. The control software measures the horizontal and vertical distance between the head restraint and the occupant’s head, and then compares this with the predetermined values. If the measured distances are outside the acceptable range with respect to the head restraint, then the control algorithm instructs the head restraint to move to the correct position. The position of the head is continuously monitored and the mechanisms are operated when an adjustment of the head restraint is necessary. The sampling frequency of the measurement of the position of the head and the adjustment of the head restraint can be chosen to avoid micro adjustments.

For testing purposes the sensors were simply attached to the head restraint foam approximately 14 cm apart facing outwards towards the head (Figure 7). In a production ready system the sensors would require a significant amount of concealment to ensure they are not susceptible to accidental damage. First the mechanical system, sensors and control circuitry were tested separately to ensure that each system was operating correctly.
To conduct the testing on the smart head restraint system as a whole, the sensors and control circuitry were fully integrated. Then the accuracy, consistency and reliability of the system has been tested repeatedly to ensure it could locate a seat occupant’s head and move the head restraint into a position that would provide protection against whiplash injuries.

The conclusion to be drawn from the testing is that the smart head restraint system concept determines the position of an occupant’s head and adjusts the head restraint to the optimum position with reasonable accuracy. The integrated sensors, actuators, control software and mechanical system worked well together.

**DISCUSSION AND CONCLUSIONS**

A full-scale, proof of concept working demonstrator of a smart head restraint system that detects and monitors the occupant’s head and adjusts to the correct position automatically was built and tested successfully. The smart head restraint demonstrator proves that the concept of a sensor-based system was entirely feasible offering an effective solution to a problem that is not currently being addressed to a satisfactory degree in the automotive industry. This system greatly increases the likelihood of the head restraint being correctly adjusted to a position at the point of impact for maximum whiplash protection with potential safety benefits and associated economic savings.

Whilst the accuracy and consistency of the prototype has been tested to a satisfactory standard, it would be beneficial to build a system to industry standards and conduct industrial trials. We demonstrated that the system has a great potential to significantly reduce whiplash injuries in rear-end impacts and we anticipate that, not in a too distant future, vehicles will be fitted with such a system.

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**REFERENCES**


5. W Wiklund and H Larsson, ‘Saab active head restraint (SAHR)-seat design to reduce the risk of neck injuries in rear impacts’, SAE Technical Paper Series 980297, Society of Automotive Engineers, Warrendale, PA.


