

New Sensors to Track Head Acceleration during Possible Injurious Events

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ABSTRACT

Instrumented earplugs were first introduced in 2000 by the Air Force Research Lab as a means of measuring head accelerations in race car drivers after it was shown that instrumented helmets slipped on the head during impact events. A version of these earplugs was adopted by the Indy Racing League and Championship Auto Race Teams (CART) in 2003. In 2006, Begeman, Melvin, Troxel and Mellor reported that signals from earplugs mounted in cadavers showed a phase shift at 50 and 100 Hz vibration indicating less than perfect coupling with the head. A new miniature tri-axial accelerometer has been developed that is small enough to be placed in the ear canal portion of communication earplugs (earpieces) as a way of improving the coupling and thus the reliability of the recordings from drivers undergoing multi-axial crash events.

The first part of the effort involved developing design specifications for the next generation earplugs. These came from Andrew Mellor at the Fédération Internationale de l'Automobile (FIA) Safety Center who developed these specifications with a view toward using the new earplugs in the F1 race series. Endevco/Meggitt proposed to develop this mini-triax which is small enough to fit in the ear canal and secured congressional funding to support the development of a manufacturing process to reliably produce the new sensor. The Air Force Research Laboratory team, who invented the first instrumented earplug, collaborated with Endevco/Meggitt to build the new sensors and provide the validation testing and comparison with the current operational sensors. The new 7273GT sensors were mounted in molded earplugs and subjected to impacts as high as 300g with very short durations in multiple axes. The earplugs were mounted in artificial ears which were mounted on rigid blocks. The sensors showed good correlation with reference sensors and demonstrated improved coupling to the head over the current generation of earplug accelerometers.

INTRODUCTION

Racecar drivers sometimes sustain a concussion during a crash. In 1998 when this research effort started there were no data recorded during such events that would relate head acceleration to the type and extent of injury. The Biomechanics Branch, of the Air Force Research Laboratory, (AFRL/RHPA) has researched human response to acceleration for more than fifty years using volunteer subjects and instrumented manikins. (See: <https://biodyn1.wpafb.af.mil>) Instrumented earplugs were introduced by RHPA in 2000 as a means of measuring head accelerations in race car drivers after it was shown by AFRL/RHPA that instrumented helmets slipped on the head during impact events. (Hill, Knox and Crockett, 2000). The initial earplugs used Endevco 7269 triaxial accelerometers developed especially for this effort by Endevco for AFRL. While the 7269 accelerometers worked they were more expensive than the race teams or sponsors were willing to pay and the 7269s required a preamplifier to interface with the Delphi ADR2 crash recorder.

At an informal group working meeting after the annual meeting of the International Council of Motorsport Sciences (ICMS) it was decided that Delphi would reengineer the earplugs using less expensive sensors from its airbag development project and that AFRL/RHPA would concentrate on testing the new earplugs on its Horizontal Impact Accelerator with human volunteer subjects. The selected sensors were less expensive and included an amplifier that facilitated connection to the ADR2. RHPA staff met with the Delphi engineers, under a Cooperative Research and Development Agreement, to share lessons learned and earplugs from the previous development. After testing during 2002, this new version of the earplugs was adopted by the Indy Racing League and Championship Auto Race Teams (CART) in 2003. Results from AFRL/RHPA were reported at SAE Motorsports conferences in 2000, 2002 and 2004 as well as ICMS and FIA meetings during that time. In 2006 Begeman,

Melvin, Troxel and Mellor (Begeman et.al. 2006) reported that signals from earplugs mounted in cadaver heads showed a phase shift at 50 and 100 Hz vibration indicating less than perfect coupling with the head. A possible solution to this problem came up in conversations with Andy Mellor (FIA Safety Institute) during the SAE Motorsports meeting. The idea was to develop a smaller sensor that could be placed deep in the ear canal portion of the earplug to help couple it to the skull. During the past year two new miniature tri-axial accelerometers have been developed that are small enough to be placed in the ear canal portion of communication earplugs (earpieces) as a way of improving the coupling and thus the reliability of the recordings from drivers undergoing multi-axial crash or blast events. The focus of this paper is to report on the initial laboratory evaluation of these new sensors and on their use in earplugs.

Previous studies have shown that the Delphi Sensor agreed well under linear impact conditions using the AFRL/RHPA Vertical Impact Device (VID) (Knox, 2002, 2003). The following plot compares the response of the Delphi Sensor in the earplug with a reference sensor when the earplug is taped to the VID carriage. Tests with the Delphi sensor mounted in an earplug inserted in a rubber ear attached to a manikin head resulted in a number of oscillations after impact. To assess the source of the oscillations one sensor/ear combination was mounted on the manikin head while another sensor/ear combination was mounted on an aluminum block attached to the carriage of the VID. As the plots in Figures 1, 2 & 3 show most of the oscillations are due to movement of the "skin" of the manikin head while the remaining oscillations are due to the earplug/ear combination. It was these observations and the recordings from race drivers that prompted Begeman et.al. to conduct the study with cadavers in which the need for better coupling between the sensors and the head was identified.

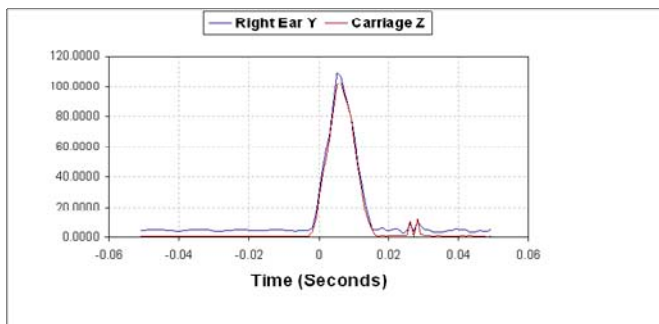


Figure 1. Delphi Sensor Response to 100 +Gy Impact (same direction as Carriage +Gz) from Knox et.al. 2004

Test of Vibration Source (Skin or Ear)

Delphi Earplugs # 1
Right In Ear on skin of Head
Left In Ear on block
Impact Is 50 - Gz

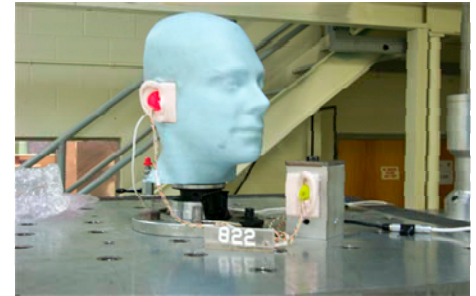


Figure 2. Test Vibration Source (skin or ear or both)

Vibration of Head, Ear or Skin

Comparison of Carriage, Head, Right Ear on skin, Left Ear on Block

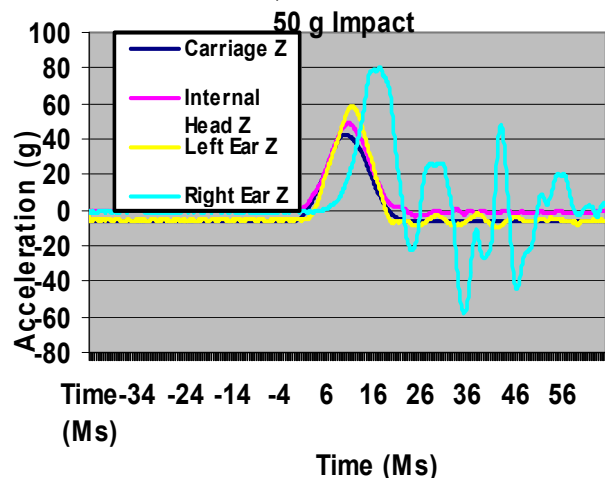


Figure 3 Plot of data from experiment depicted in figure 2. The sensor in this case was the Endevco model 7269 developed for the original earplugs. Note that most of the vibration is due to the skin of the blue head and not the rubber ear. Also note that the pulse width is longer than in the current experiments which were set up to simulate up to 1000 g in order to evaluate the model 73M1 used in shock wave tests

MAIN SECTION

METHODS

Samples of a new mini triax sensor, model 7273GT, were provided to AFRL/RHPA under a contract to develop the manufacturing process for this new, very small, sensor. The specifications were +/- 300 g, 0 – 1000 Hz with a mounted resonant frequency of 17,000 Hz. Another new sensor, model 73M1 with specs of +/- 6000 g, 0 – 20,000 Hz and a resonant frequency of 180K Hz was tested in parallel. A reference sensor, Endevco 7264C-2000 with specs of +/- 2000 g, 0 – 2000 Hz (+/- 2% max) or 0 -5000 Hz (+/- 5% max) and mounted

resonant frequency of 26K Hz.. All sensors were undamped so as to prevent phase shift.

Other sensors included:

- Delphi (Analog Devices 193) sensors used in current IRL Earplugs, 0 –250 G and resonant frequency of 24K Hz. The sensor has a built-in amplifier with 2-pole Bessel filter (-3db at 400 Hz). In the earplugs three of the sensors are mounted to measure x, y, z accelerations by being glued on an L-shaped bracket. See **Figure 4** below.
- Endevco 7269 – the original sensor built for Race Driver earplugs; +/- 500 G, frequency response 0 to 3000 Hz, mounted resonance frequency of 17K Hz_.

A Model 7273GT is shown next to IRL type earplugs – showing that it is small enough to fit in the ear canal portion. These earplugs contain an acoustic driver and three AD 193 linear accelerometers arranged in an orthogonal array.



Figure 4. Indy Racing League type earplugs made by Sensaphonics using three Delphi (AD 193) linear sensors in an orthogonal array used by AFRL subjects in a research program reported in Knox et.al. 2004. Also pictured is the new Endevco 7273GT tri-axial sensor made for studies of head acceleration – small enough to be placed in the ear canal portion of the earplug



Figure 5. The Endevco 73M1 tri-axial accelerometer with a +/-, 6K g range and resonant frequency of 180K Hz was made for AFRL for testing at the University of Virginia in a study led by Dr. Bass. It is small enough to fit in the ear canal though not as small and light as the 7273GT.

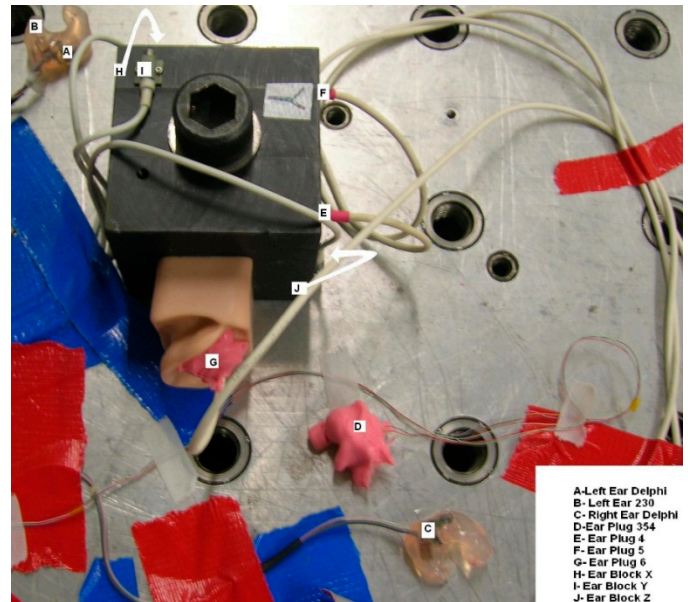


Figure 6. Reference Impact Accelerators (Endevco 7264C) on the Delrin block bolted to the carriage of the VID plus sensors mounted in a rubber ear and in earplugs held down to the carriage by tape (not shown). A – Delphi (AD 193), B – Endevco 7273GT # 230, C – Delphi (AD 193), D – Endevco 7273GT molded in ear canal portion of an ear mold, E, F - Endevco 73M1 triax in block, F- Endevco 73M1 located in ear canal portion of ear mold inserted in rubber ear, H, I & J Endevco 7264C reference sensors screwed to Delrin block which is bolted to the VID carriage. One 7264C reference sensor was screwed to the carriage (not shown).

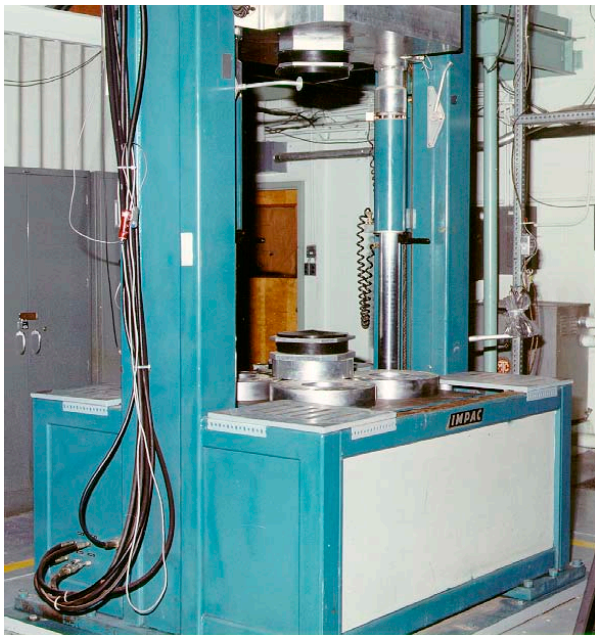


Figure 7. Monterey IMPAC Vertical Impact Device (VID) is shown with the carriage raised above the base. Rubber bumpers in this picture were replaced by stiffer bumpers and a layer of felt to obtain the desired pulse. The test device in **Figure 7** is a Monterey IMPAC Vertical Impact Device (VID) capable of producing impacts of a minimum duration of 1.6 ms and up to a maximum of 1000 g. The pulse characteristics are controlled by the drop height and the properties of the bumper materials such as elastomers, felt and mechanical shock absorbers attached to both the carriage and the impact base.

VIBRATION TABLE

Sensors were subjected to vibrations on hydraulic, pneumatic or electro-dynamic shakers to assess the introduction of phase shifts in the output of the sensors under various mounting configurations.

ELECTRONIC DATA

Data was acquired using either a DTS Pro or a DTS G5 data system with various sample rates and filter settings. DTS software was used to control the data collection and initial inspection. **Analyze Test**, software written at AFRL/RHPA, was used to filter, analyze and plot the results.

DTS Pro 8 channel DAS: 100k Hz, no filter to look at system oscillations and collect data for spectral analysis to facilitate later filtering. The large mass of the VID rings when it hits the even larger reaction mass. At high acceleration levels this ringing can set up oscillations at the resonance frequency (26K Hz) in the undamped reference sensor (7264C-2000). Proper filtering can remove these extraneous signals.

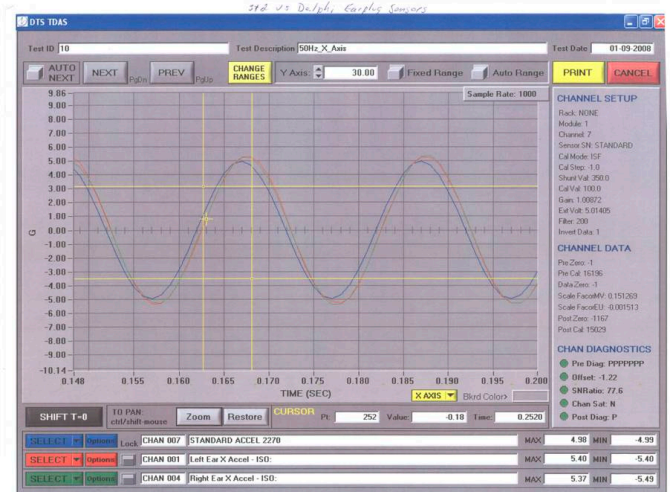
The DTS G5 32 channel DAS has a 12,500 Hz sample rate per channel, with a hardware anti-aliasing 4K input filter or 10,000 Hz with software 3K 8 pole Butterworth anti-aliasing filters. The G5 has 32 channels so many sensors could be recorded simultaneously.

The data was saved in XL spreadsheets for later processing.

RESULTS

Before receiving the new sensors for test, RHPA securely mounted a 3-axis sensor module from an IRL type earplug on a calibration shaker table. Plots of the output at two frequencies are shown in **Figure 8** below. The frequencies ranged from 50Hz to 400Hz. Notice the phase shift from 50Hz to 400Hz.

Panel A



Panel B

Figure 8. Output of Standard Reference Sensor (2270) compared with output of Delphi sensor used in the IRL earplugs. **Panel A** at 50 Hz and **Panel B** at 400 Hz. Notice the Phase shift as frequency increases.