THE DEVELOPMENT OF ACOUSTIC AND VIBRATION SENSING YARNS FOR HEALTH SURVEILLIANCE

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Acoustic and vibration measurements are useful tools for health surveillance in a number of professions. In primary industries, such as construction, workers are often exposed to significant hand transmitted vibrations (HTVs) due to power tool use, as well as high levels of noise. While monitoring solutions do exist these are often not ideal, either being uncomfortable to the wearer, or taking measurements in non-optimal locations. By exploiting electronically functional yarn technology MEMS (microelectromechanical system) sensing elements can be integrated into the core of yarns that can then be used to construct a textile. The resulting sensing yarn feels like a standard textile and can bend and conform normally making it comfortable for the user to wear. For example, a vibration sensing yarn can be integrated into the palm of work glove for HTV monitoring and will be completely undetectable to the end user. This allows vibration measurements to be taken at the point-of-entry (in the case of most power tools) providing highly representative data. In this work, ongoing developments of acoustic and vibration sensor yarns are presented along with their supporting components and data handling software.

Keywords: electronic textiles, smart textiles, vibration, acoustics, health monitoring

1. Introduction

Injuries induced by over exposure to noise or vibration are a serious concern for workers in a number of industries. Vibration can cause a variety of musculoskeletal, vascular, and neurological conditions [1] however, these largely result in one of two disorders: Carpel Tunnel Syndrome (CTS) or Hand Arm Vibration Syndrome (HAVS), often referred to as Vibration White Finger (VWF) [2]. Reported injuries vary depending on the nation, with the United Kingdom seeing an increase of 10,990 sufferers of these illness in the last ten years alone [3].

Acoustic injury can be caused by either a brief exposure to an extremely high level of noise, or a prolonged exposure to high levels of noise over a period of time. While noise related injury can manifest in many conditions [4] the two most common are Noise Induced Hearing Loss (NIHL) and tinnitus. The United Kingdom has seen an increase of 1,630 sufferers of NIHL alone in the last ten years [5].

While many nations implement strict controls over the exposure that workers can be subjected to current methodologies for monitoring and logging the exposure of workers are clearly insufficient given the prevalence of new injury cases. Vibration exposure is typically calculated with values provided by the tool manufacturer and the length of use. Acoustic exposure levels are determined using a similar estimation, where the ambient sound levels can be determined using a sound meter. In both cases this will not provide a true and accurate representation of the exposure that a worker will experience. A better method is to provide workers with personal dosemeters to measure either vibration or noise exposure.

This work focusses on demonstrating two prototype textile dosemeter garments incorporating vibration sensing yarns and acoustic sensing yarns: a vibration-sensing glove, and an acoustic sensing helmet cover. The vibration sensing glove has been developed for power tool users who are known to experience high levels of vibration, while the helmet cover was created for military applications, as military personnel are frequently exposed to high levels of noise.

The sensing elements for both devices utilise electronic yarn (E-yarn) technology, which is a technology that allows for the easy incorporation of small-scale electronic devices into the core of a textile yarn while retaining its textile characteristics such as bend and drape. E-yarns are mechanically and chemically robust and have been presented elsewhere in the literature for temperature sensing applications [6] and lighting [7].

While other wearable dosemeters exist, including the doseBadge Noise Dosemeters and the HAVWEAR monitor, textile based dosemeters offer some unique advantages. Textiles are soft, comfortable, and conformable; creating a textile dosemeter using E-yarns allows for the sensing elements to be placed anywhere on the skin. This offers a distinct advantage for vibration monitoring as the vibration sensing elements can be positioned directly where the vibrations enter the body. Acoustic sensing yarns also offer an easy way to position the sensing elements very close to the ears.

This paper demonstrates how E-yarn technology can be employed to create yarns suitable for both acoustic measurements and vibration measurements, which can then be integrated into garments. Details pertaining to the design considerations, optimisation, and the full validation of the vibration sensing yarns and acoustic sensing yarns used in this work will be the subject of two future publications. Both garments are presented in their current state of development with the vibration-sensing glove existing as a laboratory proof-of-concept (TRL 3) and the acoustic sensing helmet cover as a fully functional prototype (TRL 4).

2. Materials and methods

2.1 Electronic yarn production

In this work, the E-yarns were produced by a handcrafting process, which incorporated three major steps as outlined in Figure 1. The first step in the production process was to solder the relevant sensing element to multi-strand copper wire, which was achieved using lead-free solder paste (Nordson Corperation, Westlake, USA) and a IR spot reflow soldering system (PDR IR-E3 Rework System, PDR- Design & Manufacturing Centre, Crawley, UK). Two chips were used in this work, a three-axis accelerometer (ADXL337, Analog Devices, Norwood, USA) for vibration sensing, and a MEMS (microelectromechanical system) microphone (VM1010; PUI Audio, Dayton, USA), for acoustic sensing. In both cases a different number of interconnects need to be attached to the chip to allow for correct functionality. For the acoustic sensing yarn it was found that externally powering the chip was not necessary to collect signals (presumably due to small amounts of energy generated from the sound waves), so only two terminals were used. The vibration sensing yarn, which could collect vibration data in three axes, needed five terminals (x-axis output, y-axis output, z-axis output, ground, power in), as shown in Figure 1.

The second stage of the production process required the addition of a monofilament with a high tensile strength (Vectran™, Kuraray America Inc., Houston, TX, USA) to prevent breakages or stretching of the copper interconnects. The monofilament, solder joints, and chip was also encased within a UV curable polymer resin (Multi-Cure® 9001-E-V-3.7, Dymax Corporation, Torrington, USA). This provided mechanical and chemical protection to the chip. The resin was injected into a cylindrical Telfon mould and cured using a UV light source (BlueWave™ 50, Dymax Corporation, Torrington, USA). Given the size of the resin micro-pod, multiple applications of UV light at different angles were necessary to ensure that the resin had cured fully. In the case of the acoustic sensing yarn, a small cavity was left in the resin to allow for the correct transfer of acoustic signals.

The final stage of the production process saw the ensemble inserted within a knitted fibre sheath. For the vibration sensing yarns the sheath was produced and the resin micro-pod and copper were inserted by hand creating a final yarn with a diameter of 4.3 mm. In contrast, for the acoustic sensing yarn, the micro-pod was fed into a circular warp-knitting machine (RIUS MC braiding machine, RIUS, Spain) with four packing yarns to create a final yarn of a diameter of 6 mm.

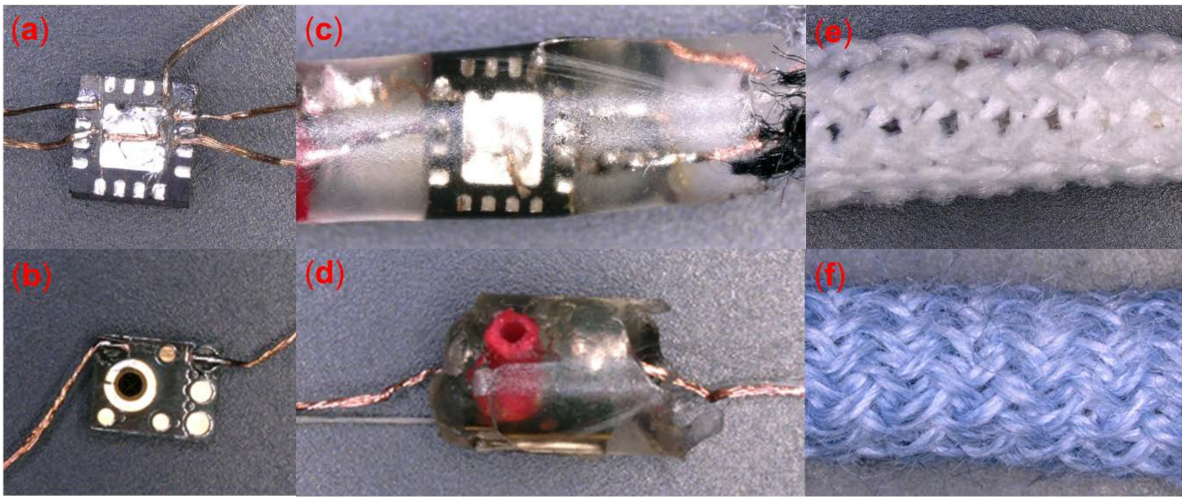

Figure 1: Microscope images of the electronic yarns at different stages in the construction process. (a) Accelerometer soldered to copper wire interconnects. (b) MEMS microphone soldered to copper wire interconnects. (c) Soldered accelerometer encapsulated within resin micro-pod. (d) Soldered microphone encapsulated within resin micro-pod. (e) Final vibration sensing yarn. (f) Final acoustic sensing yarn.

2.2 Prototype production

2.2.1 Vibration sensing glove

The vibration sensing glove prototype shown in this work differs from the device shown in other literature [7; 8], however, as with the earlier prototype, this device saw a vibration sensing yarn retrofitted to a commercially available vibration reducing work glove (Atom Corporation, Hiroshima Prefecture, Japan). After the vibration sensing yarn was produced it was embroidered by hand onto the inner knitted surface of the glove. The sensor was positioned on the palm of the hand, which is a major point-of-contact for many types of power tool. The glove was connected to a power supply (2.5 V; ISO-Tech DC power supply Model GPS-3303, ISO-Tech, Southport, UK) and computer via a sound card (Dynamode USB Sound Card; Dynamode UK Ltd., Watford, UK) to collect signals.

Figure 2: Photograph of the vibration sensing glove prototype. A commercially available vibration-reducing glove was retrofitted with a vibration sensing yarn.

2.2.2 Acoustic sensing helmet cover

A bespoke helmet cover designed for use with a standard British Army combat helmet was produced using a Shima Seiki computerised flat-bed knitting machine (SIR, 14 gauge; Shima Seiki, Wakayama, UK) from a merino wool and Kevlar mix. The helmet cover had two knitted channels on either side, above each ear, into which the acoustic sensing yarns were inserted. The acoustic sensing yarns were attached to two modified Dictaphones (Mini USB Voice Recorder, Wjiling) that allowed the signals from the acoustic sensing yarns to be recorded and stored. These hardware modules were encased within a silicone shell to improve their mechanical and chemical resilience.

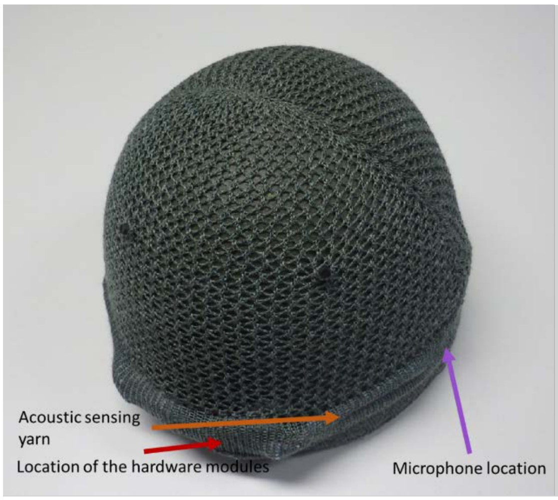

Figure 3: Photograph of the acoustic sensing helmet cover prototype on top of a British Army combat helmet. The helmet had two acoustic sensing yarns; one over each ear.

2.2.3 Processing software and signal analysis

A bespoke Python script was developed (Python v2.7; Python Software Foundation, Delaware, USA) making use of the SciPy [9], Matplotlib [10] and PyAudio [11] modules, for the collection and interruption of signals from the vibration sensing yarns. Whilst this script was capable of recording and interpreting signals from multiple soundcards (allowing x-axis, y-axis, and z-axis data to be recorded), only the z-axis is shown in this paper, for clarity. Collected signals were first fast-Fourier transformed (FFT), and then a peak-picking algorithm was applied to select relevant peaks in the data above the noise. Currently this software outputs amplitude values as a (relative) arbitrary value; however future iterations will incorporate a conversion to ms^{-2}.

Similar software existed for the acoustic sensing yarn. The Python script would read in an audio file (in the .wav format), which could be downloaded from the hardware module. The signal was FFT, a frequency correction was applied to the data to linearize the amplitude as a function of frequency which was determined from experimental work (not presented here), followed by application of an A-weighting filter. Exposure was then summed and the (relative) arbitrary value was converted into a decibel value. Finally, a time averaged exposure was calculated. In this work the signal after FFT will be shown to provide a comparison with the known output audio signal.

3. Results

The vibration sensing gloves utility was tested by one of the investigators wearing the glove and operating a pillar drill. The running pillar drill was gripped and signal from the glove was recorded. Figure 4 shows results from the glove.

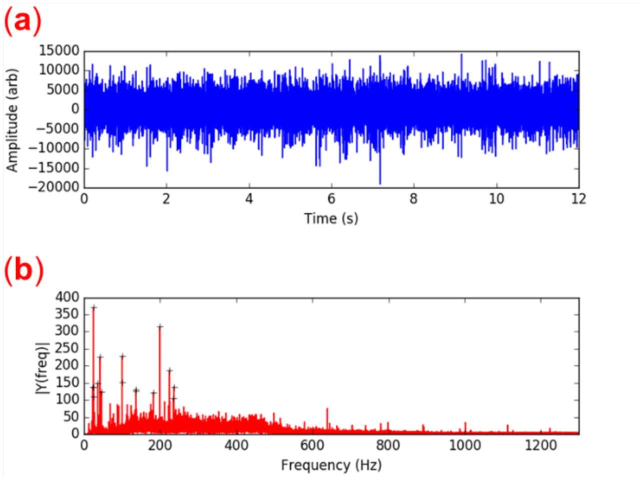

Figure 4: Vibration signal recorded when the vibration-sensing glove was gripped onto a pillar drill. (a) The raw signal. (b) A FFT of the recorded signal. The software was able to identify the main components of vibration (selected peaks are shown by a cross).

Figure 4 clearly shows that vibration data could be collected using the vibration-sensing glove, showing the functionality of this proof-of-concept device. Further work is required to refine the glove: principally the yarn should be better integrated into the glove and not embroidered onto it. Technology for the easy insertion of the yarn by incorporating knitted tubes into the textile structure at the garment manufacturing stages exists (as shown with the helmet cover) and this will be used in later prototypes. For practical applications, the glove will also require an integrated hardware module that can either store or transmit the collected signals from the yarn. Some progress has been made towards these ends and work on creating a supporting hardware module is ongoing.

Subsequently the acoustic sensing helmet cover was tested. Here the helmet cover (on top of a helmet, as shown in Figure 3) was placed next to a loud speaker (Bass Face SPL6M.2 800W 6.5 inch Mid-Bass Car Speaker, Bassface Distribution Ltd., Macclesfield, UK). A 1 kHz test frequency was played for 30 seconds. The recording that was used to generate the 1 kHz tone was analysed using the Python script described earlier, as was the recording downloaded from the acoustic sensing helmet cover (please note that the recording was shortened to 30 seconds to only include the period of time where the 1 kHz tone was playing). The spectra are shown in Figure 5.

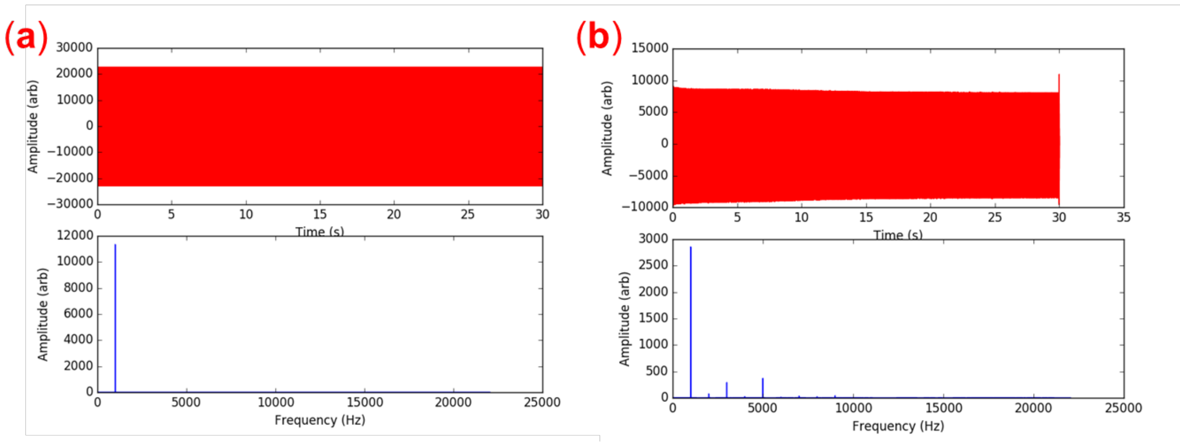

Figure 5: Acoustic signal showing the raw signal (as a function of time) above, and the FFT of the signal below. (a) The raw audio file before being played. (b) The signal recorded by the acoustic sensing helmet cover.

It can be observed from Figure 5 that the FFT of both spectra show a clear peak at 1 kHz, as would be expected. Figure 5(b) shows some additional harmonics however, this was likely due to the acoustic helmet cover picking up other acoustic signals. The raw signal showed less information due to the density of data, however both exhibited a consistent amplitude over the majority of the measurement/recording time. Unlike the vibration-sensing glove, the acoustic sensing helmet cover already had integrated supporting hardware and therefore further developments will require testing of the device in a simulated operational environment to ensure that it functions correctly over a representative range of conditions. Future work will also explore how to best produce additional helmet covers in the larger quantities required for operational testing. The process of semi-automating the yarn production process is ongoing and is currently used to produce medium quantities of light emitting yarns and temperature sensing yarns (10s to 100s). This process will need to be modified in order to produce medium quantities of the acoustic sensing yarns. Additionally a refined hardware module should be developed. While modifying Dictaphones is suitable for medium scale production (~10 helmet covers) this becomes impractical if larger quantities of helmet cover are required.

4. Conclusions

This work has presented two prototypes for health surveillance: a vibration sensing glove and an acoustic sensing helmet cover. The two devices were created using electronic yarn technology which has previously been demonstrated in the literature for temperature sensing applications [6]. This paper has focussed on displaying the technology and the full details of the yarn optimisation and validation will be disseminated at a later date.

Future work will refine both of the presented prototypes. The next generation of prototype for the vibration-sensing glove will be produced with a knitted channel for the insertion of the vibration sensing yarn and an integrated, supporting hardware module. The acoustic sensing helmet cover is a more developed prototype and further work will focus on the testing of the device and enhancing manufacturing capabilities so that additional helmet covers can be easily produced.

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