Demodulation of quasi-quadrature interferometric signals for use in the totally implantable hearing aids

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Abstract: We propose and experimentally prove an algorithm for demodulation of interferometric signals, modified for use in a totally implantable hearing aid device. A fiber optic configuration, which generates two quasi-quadrature signals by a passive 3x3 coupler, for a non-contact detection of the middle ear ossicle vibration is employed. We simulated the ossicle vibration and large movements and demonstrated the effectiveness of the algorithm to compensate changes of the signal DC values and the phase shift introduced by the coupler. Applying the proposed algorithm we obtained the output signal stability better than 0.5 dB, and the system equivalent input noise of about 31 dB (A) SPL @ 1 kHz.

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1. Introduction

The external microphone is usually employed in an implantable hearing aid, with different solutions regarding the signal transfer through the skin [1]. However, in a totally implantable
hearing aid device (TIHA), the detection of sound should be performed completely inside the patient’s body [2]. Currently, the microphone is usually subcutaneously implanted, allowing the skin to entirely cover the sensing membrane. Although the first TIHA clinical trials demonstrated 10-20 dB better functional gain, over the whole audiometric frequency, than the semi-implantable devices, a degradation of the initial sensitivity of the microphone is recognized, mainly due to the skin effect on the membrane [1]. In contrast to this approach, we propose a sound sensing system, based on a non-contact detection of vibration of the ossicles inside the middle ear (ME). The system is foreseen to be implanted into the ME cavity, as a receiving part in addition to the transducer of the cochlear- or middle-ear hearing aid. In this article we are dealing with the requirements for signal stability, low noise and low power consumption, which are, along with small dimensions, biocompatibility and encapsulation, the main issues of a TIHA device.

The interferometric principle of detection of the middle ear ossicle vibrations was already used in bulky laser Doppler vibrometers and optical coherence tomography, in ex-vivo experiments [3]. These measurements showed that the amplitudes of the ossicle vibrations are in the range from several picometers to several hundreds of nanometers [4]. Such a small amplitude, being deeply within one interferometric fringe, can accurately be measured by using the quadrature signals only, which can be obtained in many different ways. The generation method of, in this case – quasi-quadrature signals, by employing a 3x3 single mode fiber optic coupler, which has no active nor bulky components, is very suitable for implantable applications [5]. Applying relatively complex algorithms, based on the intense calculations, the acoustical signal can be separated from the environmental perturbations, assuming that they are in different frequency regions.

In this paper we address a problem of detecting small-amplitude ossicle’s vibrations in condition of a large-amplitude, quasi-DC displacement, caused by infrasound and atmospheric pressure variation. This displacement, being in the range of several hundreds of micrometers [6], influences the coupling condition of the probe beam, which, in turn, along with rotation of polarization vector, weak parasitic interferences and laser instabilities, changes the algorithm parameters which are usually supposed to be constant. Earlier proposed methods cannot be employed in TIHA, either due to the opto-mechanical constraints [7], or a lack of signal processing power [8] - related to the request for the low current consumption operation.

In order to resolve the aforementioned issues, we have modified the standard quadrature demodulation algorithm by including a mechanism for the adaptive adjusting of the parameters. The application of the algorithm to the experimentally obtained data confirms that the proposed measuring system can provide good audio characteristics, accompanied with modest power consumption. Thus, the future TIHA can be made as a very small and compact device, where the opto-electronic and fiber-optic parts would be realized in integrated optics and the electronic circuit as an ASIC with an ultra-low power microcontrollers.

2. Experimental setup

The experimental set-up is based on a modified Michelson interferometer, Fig. 1, with a 3x3 single-mode fiber-optic coupler (FOC 3x3) as a core element. The utilizing of this coupler assures a passive mean to overcome the well-known problem of signal fading, by generation of quasi-quadrature signals, thanks to its natural phase shift between two outputs of about 120°, defined by the coupler geometry. The coupler is fabricated by fusing three standard single-mode fibers SMF28, from Corning.

The interference happens between the beam reflected from the target and passing through the sensing arm (SA) and the beam reflected from the metalized fiber tip (M), and passing through the reference arm (RA). The middle output arm is immersed in the index matching gel (MG), to avoid parasitic back-reflection. The central input arm of the coupler is connected, via an optical isolator (OI), to the light source - a single-mode VCSEL diode.
at 1310 nm from RayCan. It is a telecom grade component, pigtailed to the standard single mode fiber SMF28, compatible to the coupler. The VCSEL was continuously driven by 3 mA, emitting about 500 µW of optical power, which is tissue-safe in continuous operation [9]. Two InGaAs photodiodes (PD-X, PD-Y), DC coupled to two transimpedance amplifiers, provide the pair of quasi-quadrature signals. The signals were acquired by a 16-bit NI DAQ card at rate of 100 k Samples/s and stored for off-line processing.

![Experimental set-up](image)

**Fig. 1.** Experimental set-up: FOC 3x3-fiber optic coupler, VCSEL-optical source, OI-optical isolator, PD-photodiodes, DAQ-acquisition card, MG-index matching gel, SA-sensing arm, RA-reference arm, PZT-piezotransducer, MTP-motorized positioner, M-mirror, SG-signal generator.

The target (inset of Fig. 1) was a piece of retro-reflecting tape of about 250x250 µm in size, fixed to the incus ossicle, in order to increase its reflection. Previously, we found that the reflection of the incus itself is only 2%; also, the reflection is very instable while the incus is moving under the atmospheric pressure changes. From technical and surgical point of view, there is no limitation of using such a small retroreflector in a real implantation [10]. The incus was attached to a calibrated PZT rod, mounted on a motorized scanning stage (MTP). The PZT rod was driven by a sinusoidal voltage source (SG), in order to simulate vibrations of the ossicle. The ossicle was vibrating at 1 kHz, with an amplitude of 7.4 nm (calibrated by a Polytec vibrometer), for the sake of algorithm validation. Although other signal forms can be used, we performed experiments only at this, standard testing frequency [11], since the algorithm is no frequency dependent. The scanning stage provided a linear displacement over 500 µm, with the constant scanning speed of 25 µm/s.

According to [6], the settled amplitude of the target vibration corresponds to 72 dB SPL@1kHz, and the stage movement simulates the change of atmospheric pressure of 5 mmHg (the maximum pressure difference before the Eustachian tube automatically opens). Two photodetector signals were recorded during the 20 s scan, while the target was vibrating.

### 3. The algorithm

The signal processing algorithm starts with the equations describing the raw photodetector signals:

\[
V_{PDX}(t) = X_{DC} + X_A \cos \left( k \left[ V \sin \omega t + L(t) \right] \right) \\
V_{PDY}(t) = Y_{DC} + Y_A \cos \left( k \left[ V \sin \omega t + L(t) \right] + \Psi(t) \right)
\]

Where \(X_{DC}\) and \(Y_{DC}\) are the signal DC levels, which include the steady light intensities and different offsets from the transimpedance stages; \(X_A\) and \(Y_A\) are amplitudes of the interferometric term, \(V\) is the amplitude of vibration; \(L(t)\) is the trajectory of the motorized stage and \(\Psi(t)\) is the phase shift between the interfering waves. The goal of the signal
processing is to extract the target vibrational signal ($V \sin \omega t$), i.e. to exclude the influence of all other time varying factors - $L(t)$ and $\Psi(t)$.

The first step of the processing is removing the DC offsets and performing normalization of the two raw interference signals:

$$SX(t) = \left( V_{pix}(t) - X_{DC} \right) / X_a = \cos(k[V \sin \alpha t + L(t)])$$
$$SY(t) = \left( V_{pix}(t) - Y_{DC} \right) / Y_a = \cos(k[V \sin \alpha t + L(t)] + \Psi(t))$$

This step assumes knowledge of four parameters: $X_{DC}$, $Y_{DC}$, $X_a$ and $Y_a$. These parameters depend on the light intensities and the fiber-to-target coupling ratio – they are not constants. There is, however, no real need to know the exact values of amplitude of interferometric term, $X_a$ and $Y_a$. It is evident from (3) that it is sufficient to make them equal ($X_a = Y_a$), by adjusting the gain of transimpedance amplifiers. The change of the DC levels can be determined by tracking in real time the mean between the local maxima and minima of photodetector signals. The detected extrema are slowly leaking/rising with a predefined time constant. Using trigonometric identities, a simple manipulation with (2) gives:

$$\tan\left(k [V \sin \alpha t + L(t)]\right) = \frac{SX(t) \cdot \cos(\Psi(t)) - SY(t)}{SX(t) \cdot \sin(\Psi(t))}$$

(3)

Since $\Psi(t)$ cannot be considered as a constant, it should be found out for certain time intervals during which it has a relatively stable value. The phase shift $\Psi_n$ belonging to the n$^{th}$ interval can be calculated at the moment when the ellipse has its maximum radius:

$$\Psi_n = \tan^{-1}\left(\frac{SX(t_n)}{SY(t_n)}\right) \quad \text{at} \ t_n \ \text{when} \ SX^2(t_n) + SY^2(t_n) = \text{max}$$

(4)

An additional constraint is that the pair of signals SX and SY are located in the II quadrant. The calculated phase shift $\Psi_n$ can now be included in (3) and used further, until the next interval and the moment $t_{n+1}$, when the new $\Psi_{n+1}$ will be calculated. The process of computing of $\Psi_n$ is performed only for ellipses, when the running ellipse eccentricity exceeds a certain threshold value. The processing continues with calculation of the four-quadrant second order polynomial arctangent approximation [12], then with the removing of 2$\pi$ phase wraps and ends up with the band-passing of the audio-range 125 Hz-8 kHz, which removes out $L(t)$ - a slow displacement of the motorized stage.

Regarding the phase shift, the key factor for a smooth acoustical output is the same as in the case of DC levels determination – the optimal time window and fading time for finding the local extrema. In our experiments, these time constants were straightforwardly chosen due to continuous scanning, where the extrema have regularly been appearing every $\sim 2.5$ ms. In fact, the time window and fading time could be correctly chosen only in in-vivo experiments, because the movement of ossicles cannot be fully predicted, based on the knowledge of the atmospheric pressure changes. However, our experiments show that, when the target is slowly moving - like an incus under the variation of the atmospheric pressure, a relatively wide range of time constants provides an acoustical output of required stability.

4. Results

The raw interference signals in Lissajous representation are shown in the left side of Fig. 2. It is clear that the phase shift between the signals - the slope of the ellipse in the actual interferometric fringe, is not a constant (i.e. equals to 120°), as it is expected. While the target is moving, the slope is apparently changing, from about 99° to 144°. Simultaneously, as can also be seen in Fig. 2, the “center” of the ellipse, which corresponds to the DC levels of photodetector signals, is changing its position. We applied the described algorithm to these pair of raw signals and got- the time varying DC levels, calculated as the running middle of
the signal extrema, and the change of the coupler phase shift, which are presented in Fig. 2, versus the target position. In a set of successive identical experiments, these curves were slightly different, but roughly within the limits shown in the right graph in Fig. 2.

![Fig. 2](image)

**Fig. 2.** Lissajous representation of two raw quasi-quadrature photodetector signals (left) during 20 s of simultaneous target vibration and moving. The ellipses, representing the minimum and maximum coupler phase shift, are labeled. The corresponding variations of the 3x3 coupler phase shift and changes of the DC levels, during the 500 μm long scan, calculated by the proposed algorithm, are shown in the right graph.

The amplitude spectral density of one of the raw photodetector signals is shown in the left graph in Fig. 3. A distinctive peak at about 39 Hz, equals to the Doppler shift, corresponds to the main modulation – the sweep through the successive interferometric fringes. The peak of the incus vibration at 1 kHz is almost completely suppressed; only its sidelobes at 960 Hz and 1040 Hz (see the inset) are clearly visible. It is evident that a simple filtering of one of photodetector signals cannot extract the useful audio signal. Thus, a complex demodulation technique, such as here proposed algorithm, has to be applied.

![Fig. 3](image)

**Fig. 3.** The amplitude spectral density of one of the raw photodetector signals (left) and the output audio signals, before and after the A-weighting (right). The output audio signal is obtained by using the proposed algorithm, where the coupler phase shift and photodetector signal DC values are dynamically adjusted.

The amplitude spectral density of the final result of signal processing, acoustical signal before and after the A-weighting filtration, is presented in the right graph in Fig. 3. A clear peak, corresponding to the 1 kHz incus vibration, is now the most prominent one, quite opposite to the spectrum shown in the left. There are still some residual modulations at the fringe frequency, which can be noticed as the sidelobes around 1 kHz. However, they are suppressed by more than 40 dB below the main peak. The two low-frequency peaks appearing at about 180 Hz and 450 Hz are associated to the mechanical vibrations in the laboratory. The
total noise, calculated by integration of the amplitude spectral density of A-weighted spectrum in Fig. 3, across the audio range 125 Hz-8 kHz, is about 50 pm rms. This value corresponds to about 31 dB SPL (A) @ 1 kHz [3], which can be considered as the equivalent input noise, close to the values of commercially available hearing aids [13].

The waveform of the final acoustic signal, after bandpass filtering in the 125 Hz-8 kHz range, is presented in Fig. 4. For comparison purposes, the result of the processing based on the classical assumption $\Psi = \text{const.} = 120^\circ$, is also shown in the same graph.

From the figure zoom-in inset, it is evident that the classical assumption gives an unstable acoustical signal, with a variation of amplitude exceeding 6 dB. On the contrary, the signal obtained using the adjustable phase shift and DC levels, has relatively stable amplitude, with a variation within 0.5 dB. This variation is quite acceptable because it is below the human just-noticeable difference of 1 dB [14].

5. Conclusion

An algorithm for demodulation of interferometric signals, which compensates the permanent changes of the phase shift introduced by a 3x3 fiber optic coupler, and the changes of signal DC level in a TIHA device, has been presented. The algorithm is relatively simple and can be performed using an ultralow power microcontroller, keeping the total power consumption of the device, including the VCSEL current, inside several milliamps. In the experiment where a very small vibration of the incus is simulated simultaneously with its large and slow displacement, we have shown that the final processed audio signal maintains a very stable amplitude. Since the system also has an acceptable equivalent input noise, all these characteristics make the proposed technique promising to be used in a TIHA device. Further investigation will be based on the results from \textit{ex-vivo} experiments, carried out on a cadaver sheep’s incus under acoustical excitation, in a real atmospheric pressure environment.

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