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An articulated predictive model for fluid-free artificial basilar membrane as broadband frequency sensor

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ABSTRACT

In this article, an extremely versatile predictive model for a newly developed Basilar meta-Membrane (BM^2) sensors is reported with variable engineering parameters that contribute to it's frequency selection capabilities. The predictive model reported herein is for advancement over existing method by incorporating versatile and nonhomogeneous (e.g. functionally graded) model parameters that could not only exploit the possibilities of creating complex combinations of broadband frequency sensors but also explain the unique unexplained physical phenomenon that prevails in BM^2, e.g. tailgating waves. In recent years, few notable attempts were made to fabricate the artificial basilar membrane, mimicking the mechanics of the human cochlea within a very short range of frequencies. To explain the operation of these sensors a few models were proposed. But, we fundamentally argue the "fabrication to explanation" approach and proposed the model driven predictive design process for the design any (BM^2) as broadband sensors. Inspired by the physics of basilar membrane, frequency domain predictive model is proposed where both the material and geometrical parameters can be arbitrarily varied. Broadband frequency is applicable in many fields of science, engineering and technology, such as, sensors for chemical, biological and acoustic applications. With the proposed model, which is three times faster than its FEM counterpart, it is possible to alter the attributes of the selected length of the designed sensor using complex combinations of model parameters, based on target frequency applications. Finally, the tailgating wave peaks in the artificial basilar membranes that prevails in the previously reported experimental studies are also explained using the proposed model.

1. Introduction

Band pass frequency sensors, if systematically designed will have diverse applications in the different fields of science and engineering. For example, starting from the micro mechanical devices, in manufacturing instrumentations, 3D printing, in micro-electronic devices, photonic and phononic devices, to the multi species biological sensing, chemical sensing and in applications of microfluidics will have transformative opportunities using band pass frequency sensors which are currently not perceived. Here we classified the frequency sensors into two broad categories; (1) Single frequency sensors, and (2) Broad Band sensors (also known as band pass sensors). In case of single frequency sensors a unique frequency is sensed by the sensor at its peak response [1]. Whereas, in band pass sensors, several bands of frequencies are mechanically sensed

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to find the frequency content in the input signal. This is similar to the concept of Mechanical Fourier Transformer (MFT). Alternatively, it can also be said that these band pass sensors are designed to filter the frequencies beyond the frequency of interest, mechanically.

Currently, in the design of broadband sensors, series of cantilever beams with proof masses are used where the first resonance frequency of the beams are sensed individually. These sensors detect the shift in the resonance frequencies of the beams to facilitate the analysis of the target parameters [2–8]. Battiston et al. [9,10] presented a chemical sensor based on an array of eight silicon cantilever beams. All cantilevers are glazed on one side with a chemo-markers that display distinct response to the target analyte molecules. When the sensor layer is exposed to the analyte, the surface stress, beam mass or proof mass changes and the resonance frequencies are shifted. A similar class of bio-chemical sensors are also presented by Moulin et al. [7] that can absorb bio-chemical species on the functionalized surface of a micro fabricated cantilever and cause surface stress. In the past few years, biosensors have received substantial attention from the research community. Monitoring of a specific matter/molecules is an important aspect in bio-chemical applications, ranging from the clinical analysis to the environmental control to the monitoring of numerous industrial processes [6,11–13]. Zhu et al. [1] proposed a piezoelectric micro cantilever sensor to detect humidity from the shift in the resonance frequencies due to the change in the young's modulus of the cantilever beams. Hodnett et al. [14] describes a broadband acoustic sensor to evaluate the acoustic emissions from the cavitation effect produced by a typical commercial 20 kHz sonochemical horn processor.

In the recent years, band pass sensors/filters are also introduced in energy scavenging. Powering the low power electronic gadgets were envisioned by harvesting energies on the go, from the environmental noises and human processes like walking, running, hiking, etc. Previously a design of an energy scavenger was demonstrated where the resonant frequency of the device coincides with the peak-power frequency of the dynamic source [15]. However, if a mixture of peak-power frequencies coexist in the source signal, it is quite challenging to manufacture multiple energy scavengers to harvest energies at the peak frequencies, simultaneously. Therefore, in such instances, within the range of peak-power frequencies an energy scavenger that is expanded to the broader frequency bandwidth should be an appropriate choice. A device with such frequency bandwidth is a mechanical band-pass sensor or a filter. Earlier, cantilever design of band pass filters is proposed by Shahruz [16–18]. In those studies, the band pass filters are designed by varying the dimensions of the beams and the proof masses, systematically. Besides the cantilever design of band pass sensors, fixed beam band pass sensors were also presented in recent publications [19]. Please note that the broadband terminology herein, refers to the band in terms of thousands of Hz i.e. 10^3 order. Hence, the research related to the broadband sensors or harvester's operative in the range of 10 or 10^2 order of frequencies are not reviewed.

Next we review the design of artificial basilar membrane in this paragraph. To recover the hearing deficiency, cochlea implantation is essential if the inner ear is damaged. The key functions of the cochlea are not only to convert the acoustic pressure into the electrical signals, but also to spatial select the frequencies [20]. Basilar membrane (BM) is a biological diaphragm plays the most important role in a human cochlea. BM has a natural variation of the mechanical properties and the boundary conditions from the basal to the apical end (see Fig. 1). By virtue of the graded material and geometric properties, BM is capable of spatially selecting the sonic frequencies. When an input signal has mixed frequencies, the local resonance dominates at different locations on the BM and using hair cells the respective frequency is sensed mechanically [21].

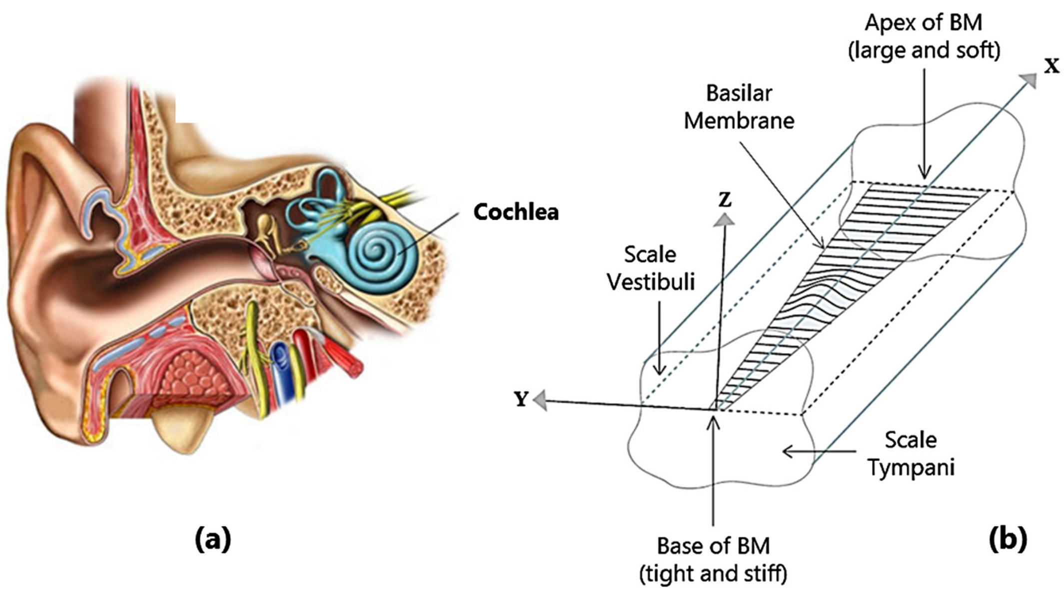

Fig. 1. (a) Cochlear orientation in human ear and (b) schematic representation of the unrolled cochlea.