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Using nano-micro-control technology to improve breathing pressure in vocal music technique teaching innovation

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Abstract. In the present study, we aim to use nanotechnology sensors/actuators to capture pressure and frequency of voice singers and to send signals for improving breathing pressure. In this regard, a circular composite structure having 3 different layers are used. The core layer is nano-composite material reinforced with graphene nanoplatelets. The face sheets are piezo electric materials connected to electrical circuit capable of measuring and applying voltage to the piezoelectric layers. This sensors have extremely smaller size than conventional sensors attached to the neck of singer and, hence, minimizes the influences on the output voice of the singer. A brief theoretical framework are presented for nonlocal strain gradient theory and geometry of the sensor is described in detail. The controlling procedure along with experimental results on 20 amateur and professional singer participants are also presented. The results of the study indicate that the participants could gain benefit from the device for improving their ability in phonation and keeping their frequency at a constant level although they have difficulty in the beginning of the experiment getting used to the device.
Keywords: ANN; breath pressure control; nano-sensors; subglottal pressure; vocal music; voice frequency

1. Introduction

Controlling breath in vocal music is one of the challenging parts in practicing and training sessions. Indeed, it is the ground skill in singing and vocal music (Dai *et al*. 2023, Peng *et al*. 2023, Sabzevari *et al*. 2023, Yang *et al*. 2023, Zhao *et al*. 2023, Zheng *et al*. 2023). The beginners in the vocal music take several months at their early stages of their training working on the breathing and strengthening muscles related to inhale and exhale. Monitoring of the breathing ability in its conventional way is performed mostly by sound recording devices and hearing by teachers. However, digitizing and analyzing the breathing ability could aid the trainees to advance more rapidly in their vocal music learning process (Habibi *et al*. 2016, 2018a, b, 2019b, d, e, Ebrahimi *et al*. 2019a, Esmailpoor Hajilak *et al*. 2019, Pourjabari *et al*. 2019, Safarpour *et al*. 2019a, Zhu *et al*. 2022, Dai *et al*. 2023, Zheng *et al*. 2023).

Sensing the movement of body during breathing and singing has been the center of attention of many studies to capture the efficacy in singing as function of breathing patterns. In this regard, Pettersen *et al*. (2005) used several sensors to monitor the change in the upper and lower thorax as well as muscle engaged in the singing and speaking of eight participants. They utilized different types of sensors in different locations of the body. On the neck and shoulder muscles ambulatory four-channel monitoring system and for measuring change in circumferences of the thorax used strain gauges. Using macro size sensors in singing practices influences the singing and the voice of the singer and vocal trainees. In another study, Reed *et al*. (2022) devises and novel soft knit sensing devise using knitting collar. On the inside of the collar, several surface electrography sensors were attached. The main objective of the study was to propose new comfortable collars maintaining rigid sensing using conventional electromyography (EMG) sensors (Fazaeli *et al*. 2016, Habibi *et al*. 2017, 2019a, c, Safarpour *et al*. 2018, 2019b, 2020, Alipour *et al*. 2020, Ebrahimi *et al*. 2020a, Ghazanfari *et al*. 2020, Chen *et al*. 2022). For detecting movement of tongue during articulation of consonant production, (Katz *et al*. 2014) utilized magnetometer system attached to the upper surface of tongue. It is clear that using such system having large size sensors in comparison to the internal space of mouth and also including wiring system considerably affect the consonant production. However, since the study was focused on the movement and position of tongue in articulating different consonants, the results receive limited influence in this regard. On the other hand, as the authors claimed, most of the participants got used to the system within few minutes. Piao and Xia (2022) proposed a new device for measuring change in the twin ribs, back waist and abdomen. The wearable device integrated with a software to detect the state of breathing and singing pitch. It was utilized by participants with different backgrounds. In the group with no musical background the device let to ~20% improvement in the pitch accuracy in singing. Angelakis *et al*. (2021) engaged a multi-sensor system to find correlation between different vocal mechanisms function and output of voice in two professional singers.

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They utilized four sensors for capturing the three factors of the participants including voice output, phonatory function and respiratory responses. Different methods of analyzing demonstrated high correlation between different factors. In another study, Aaen *et al*. (2021) considered effect of air adding to the voice on the pressure level of voice and energy of the fundamental frequency along with several other parameters. They utilized several sensors including imagining camera system, electroglottography and acoustic signals. The results indicated that using the air added technique a larger gap between vocal folds was observed. Moreover, adding air results in the lower level of voice pressure.

In most of the vocal studies, electroglottography sensors are used to find out about the state of contact between vocal folds. However, the considerable size of this devices usually affects the performance of the singer. For delicate analysis, even small effects on the vocal performance could mislead the analysis. Therefore, other type of sensors are required with smaller size and interruptory effects on the singer voice. Small scale sensors like micro- and nano-size sensors have been focus of attention in the recent decade. These devices have found application in healthcare system, vibration analysis, drug delivery and also in the force measurement and analyses (Al-Furjan *et al*. 2020w, Naderi *et al*. 2020, Habibi *et al*. 2021b, c). Recent developed motion nano-sensors are constructed using sandwich composite structure having a nanocomposite core and one or two layers of piezoelectric material aiming to receive vibration and induce motion. The capability of piezoelectric to convert electrical field to mechanical motion is exceptionally useful in the controlling of vibrations. In this regard, Kargarnovin *et al*. (2007) utilized piezoelectric material to control vibration in a functionally graded plate structure. They observed that using feedback electrical control system, the vibration stability of the system could be significantly increases. Duo to emergent of the small size effects in the nano-scale structures, classical theories of continuum mechanics are barely capable of reflecting mechanical behaviors. Therefore, nonclassical models are widely utilized in the small size devices. Mahinzare *et al*. (Mahinzare *et al*. 2019) utilized nonlocal strain gradient theory to study vibration behavior of circular nano-scale plate under different loading type. Effects of different material and geometrical parameters were reported. Ebrahimi and Barati (2017) employed nonlocal strain gradient theory to analyze vibration of nano-scale plates on viscoelastic substrate. It was fund that using different external voltage values on the piezoelectric layer different responses in vibration of the plate could be obtained. Knowing this behavior of nano-scale structures equipped with piezoelectric material, it is possible to design a device to excite mechanical motions for the aim of controlling and sending mechanical signals. Habibi *et al*. (2021c) examined the wave propagation behavior in cylindrical structure integrated with piezoelectric layers using nonlocal strain gradient theory. The composite structure was a laminated composite. The results of their study indicated that the wave propagation behavior is influenced by several parameters including geometry and material properties of the structure (Han *et al*. 1997, Pietrzakowski 2008, Liew *et al*. 2015, Farajpour *et al*. 2017, Singh and Panda 2017, Al-Furjan *et al*. 2022). There are numerous articles on the correlation between subglottal pressure and voice frequency. Atkinson (Atkinson 1978) utilized experimental measurement of six factors and frequency of voice to detect correlation between these factors and voice frequency. It was found that at low voice frequency the subglottal pressure is the most important parameter controlling frequency. At high frequencies, laryngeal tensions are more influential than other parameters. Later studies confirmed the results obtained by Atkinson (Alipour and Scherer 2007, Wang *et al*. 2021)

Artificial intelligence method (Ebrahimi *et al*. 2019b, c, 2020b, Hashemi *et al*. 2019, Moayedi *et al*. 2019, 2020a, b, Mohammadgholiha *et al*. 2019, Mohammadi *et al*. 2019, Habibi *et al*. 2020, Oyarhossein *et al*. 2020, Shariati *et al*. 2020a, b, Shokrgozar *et al*. 2020) aids the scientists and engineers to bypass experimental and numerical methods and analyses and obtain satisfactory results in short time in many fields of study (Amelirad and Assempour 2019, 2021, Habibi *et al*. 2021a, Moradi *et al*. 2022a, b). In this regards, several approaches have been proposed in the literature in the field of health care systems and predicting human body responses (Kantarjian and Yu 2015, Rabbani *et al*. 2018, Yu *et al*. 2018).

In the present study, we aim to use nanotechnology sensors/actuators to capture pressure and frequency of voice singers and to send signals for improving breathing pressure. In this regard, a circular composite structure having 3 different layers are used. The core layer is nano-composite material reinforced with graphene nanoplatelets. The face sheets are piezo electric materials connected to electrical circuit capable of measuring and applying voltage to the piezoelectric layers. This sensors have extremely smaller size than conventional sensors attached to the neck of singer and, hence, minimizes the influences on the output voice of the singer. A brief theoretical framework are presented for nonlocal strain gradient theory and geometry of the sensor is described in detail. The controlling procedure along with experimental results are also presented.

2. Methodology

2.1 Sound production in human vocal folds

The main organ in human body to produce sound is larynx. This organ along with other organs i.e. lung, mouth, etc (Hashemi *et al*. 2019, Al-Furjan *et al*. 2020e, o, q, s, Bai *et al*. 2020, Cheshmeh *et al*. 2020, Li *et al*. 2020a, Lori *et al*. 2020, Najaafi *et al*. 2020, Shariati *et al*. 2020c, Xiong *et al*. 2020, Guo *et al*. 2021b, Liu *et al*. 2021a). work together to produce sounds with different pitches and strengths. The structure of larynx is illustrated in Fig. 1. The voice is produced by vibration in vocal folds as a result of air flow from subglottal area. This mechanism is very likely similar to the flutter phenomenon in the aerodynamics (Deguchi 2011). Therefore, several parameters are engages in the

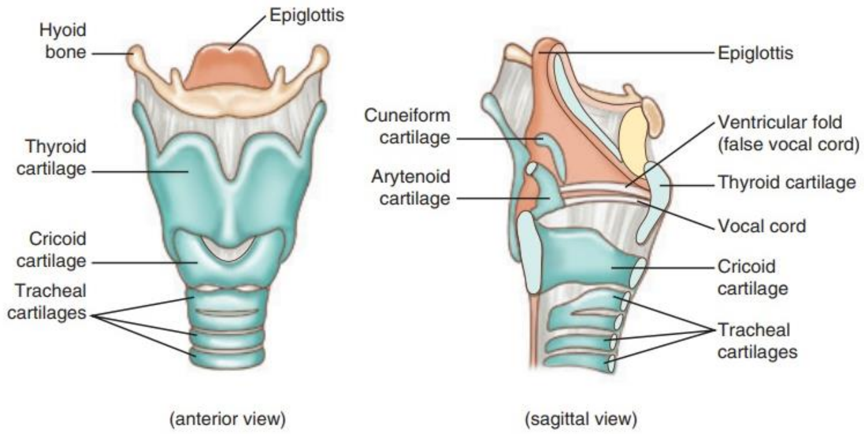


Fig. 1 Human larynx structure

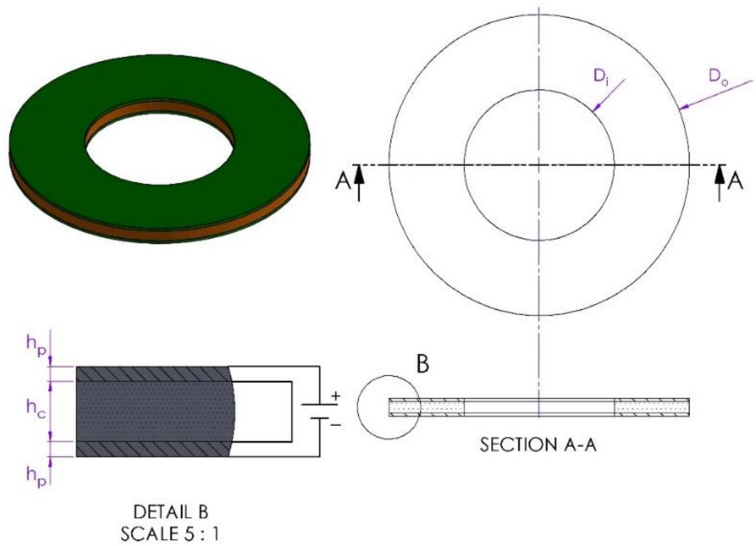


Fig. 2 Geometry of the main part of nano-sensor in shape of an annular plate

frequency of the voice. The first parameter to consider is the subglottal pressure value which is vital parameter determining the air flow velocity through vocal folds. Controlling pressure is conducted mainly by muscle around lung area as well as neck muscles.

One another parameter in controlling the frequency is the stiffness and damping of the muscles in larynx area. With stiffer muscles the frequency of the voice increases keeping all other conditions intact. There are some other geometrical condition influencing frequency of the voice which we are omitted in this study. We will focus on the effects of subglottal pressure on the frequency of voice and how to send signals to the trainees in adjusting their phonation (Adamian *et al*. 2020, Al-Furjan *et al*. 2020c, d, Li *et al*. 2020b, Liu *et al*. 2020a, b, 2021b, Wang *et al*. 2020, Zare *et al*. 2020, Zhou *et al*. 2020, Dai *et al*. 2021ab, Guo *et al*. 2021a, Habibi *et al*. 2021a, He *et al*. 2021, Huang *et al*. 2021a, Shao *et al*. 2021, Wu and Habibi 2021, Zhang *et al*. 2021, Kong *et al*. 2022).

The details of the larynx in Fig. 1 shows several cartilages, bones and muscles which aim to control length, opening and stiffness of vocal folds. The larynx is located above trachea and limited to the hyoid bone in its upper section. Two main components exist in the larynx: couple components and single ones.

2.2 Frequency analysis using nanotechnology sensors

The geometry of nano-sensor is demonstrated in Fig. 1. This geometry shows the main part of sensing and actuating device designed to capture the frequency of the voice in the participants. This sensor/actuator is a simple annular plate with two piezoelectric layers at the top and bottom faces coupled together with electrical circuit. In addition, the core material is made from carbon nanotube (CNT) reinforced composite material (Hou *et al*. 2021, Liu *et al*. 2021c, Dong *et al*. 2022, Fan *et al*. 2022a, b, Hu *et al*. 2022, Huang *et al*. 2022, Luo *et al*. 2022a, b, Moradi *et al*. 2022c, Wang *et al*. 2022b, c, 2023, Yang *et al*. 2022a, b, Zhang *et al*. 2022, Zheng *et al*. 2022, Zhou *et al*. 2022a, Fang *et al*. 2023, Jin *et al*. 2023). This nano-structured component is able to transform mechanical deformation to electrical voltage and vice versa. This ability makes it possible to convert mechanical vibration to electrical waves and analyzing

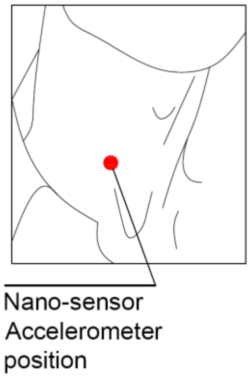


Fig. 3 Position of nano-sensor/actuator on the neck-surface near subglottal area

through computers would be much easier and more effective in term of time. On the other hand, with swift mathematical analyses a feedback could be provided by generating voltage leading to mechanical vibrations. In this manner, both of controlling and sensing voice signals could be performed using single sensors.

2.3 Subglottal pressure measurement and its control

In the present study, the subglottal air pressure is estimated using the procedure introduced and described in Fryd *et al*. (2016). In this regard, the accelerometer nano-sensors are utilized to capture movements in the neck-surface. Studies show that the estimated values of the subglottal air pressure could be measured with high accuracy. On the other hand, the noninvasive nature of this measurement reduces the negative effects on the voice production procedure during experiments. Fig. 3 illustrates the position of the nano-sensor on the neck-surface. In this position it is possible to estimate both subglottal air pressure as well as voice frequency (Mehta *et al*. 2016). However, we will utilize this nano-sensor to estimate subglottal pressure (Huang *et al*. 2021b, Jiao *et al*. 2021, Ma *et al*. 2021, Moradi *et al*. 2021, Xu *et al*. 2021, Zhao *et al*. 2021, Michael *et al*. 2022, Yu *et al*. 2022, Zhou *et al*. 2022b).

3. Experiments

Ten professional (5 men and 5 women) singer were asked to perform some phonation tasks during testing. They were asked to sing \a\, \ie\ and \u\ phonations in 5 seconds intervals with high and low pitch. During this time the sound frequency were recorded using microphone and the pressure was estimated using nano-sensor/actuator accelero-meters. Therefore, putting these measurements together it become possible to find a correlation between the quantities.

4. Artificial neural network (ANN) modeling

The artificial neural networks have shown to be a promising modelling method for complex behavior of wide variety of systems from mechanical system to chemical processing (Fan *et al*. 2022a, Luo *et al*. 2022b, Wang *et al*. 2022a, Xia *et al*. 2022). The main role of the artificial intelligence is to predict the next response of systems and to provide information for proper response of the system. In the present, study, we designed a neural network to predict the effects of both subglottal pressure P and its rate dP/dt on the voice frequency in vocal music. This includes decreases and increases in the frequency in different cords and how they are related to the subglottal air pressure parameters. In this regard, we specifically interest in the high pitch and low pitch of the voice productions.

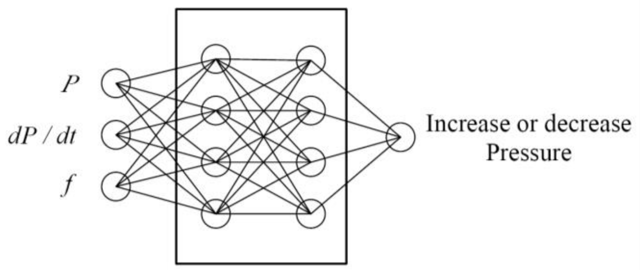


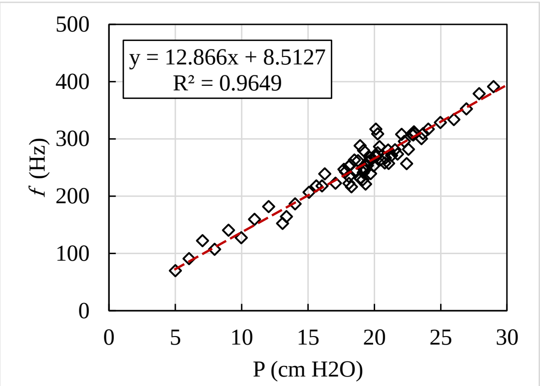
Fig. 4 Schematic of neural network with three inputs and one output

The structure of the ANN is depicted in Fig. 4. It is seen, this network has three inputs of subglottal air pressure P, rate of subglottal air pressure dP/dt and the pitch or frequency f of the sound. The output is the signal to increase pressure or to decrease it which is utilized to send signal the vocal music trainee. Using this method, the trainee knows at each point of singing to control the air pressure. The middle layers have 50 nodes each. The Scikit-Learn package in Python is utilized in this study to perform ANN modeling.

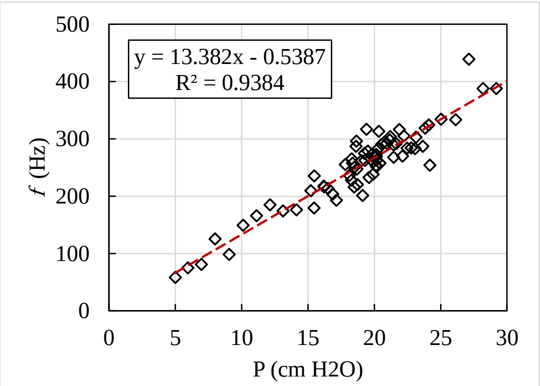
The algorithm used here for optimization of the supervised network is the gradient decent. This algorithm a very efficient one in minimizing convex loss functions. The loss function in the present study is taken to be the mean squared error (MSE) with the following relation (Arabnejad Khanouki *et al*. 2010, Mojtaba 2011, Shariati *et al*. 2011a, b, 2019a, b, c, d, e, 2020d, e, f, g, h, 2021, Sinaei *et al*. 2011, 2012, Mohammadhassani *et al*. 2013, 2014, Mansouri *et al*. 2016, Safa *et al*. 2016, Shahabi *et al*. 2016, Toghroli *et al*. 2014, 2016, Khorramian *et al*. 2017, Nosrati *et al*. 2018, Chahnasir *et al*. 2018, Sedghi *et al*. 2018, Ziaei-Nia *et al*. 2018, Katebi *et al*. 2019, Milovancevic *et al*. 2019, Sajedi and Shariati 2019, Trung *et al*. 2019a, b, Afshar *et al*. 2020, Safa *et al*. 2020, Yazdani *et al*. 2020, Davoodnabi *et al*. 2021):

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(r_i - \hat{r}_i)^2 \quad (1)$$

In the above equation, the parameter N is the number of total data fed into the ANN. The actual value of the parameter is denoted by r_i and the predicted value by ANN is $\hat{r}_i$. The ANN tried to minimize MSE value with adjusting its internal parameters (Al-Furjan *et al*. 2020a, b, g, f, h, i, j, k, l, m, n, p, r, t, u, v, 2021a, b).



(a) Men



(b) Women

Fig. 5 Correlation between subglottal pressure and voice frequency for D4 note. (a) for men singers and (b) for women singers

5. Results

In this section the results obtained from experimental tests and ANN modeling is presented.

5.1 Experimental results

The results of subglottal pressure measurement using nano-sensor and voice frequency of the participants are presented in Fig. 5. As seen in this figure, for most of the data collection periods the frequency were kept near D4 note equivalent to 277Hz for both men and women group. This frequency is asked to keep during phonation and the singers tried their best to hold the frequency. On the other hand, the pressure during the phonation was also kept at the same level. However at higher pressure (start of the phonation) and at the low pressure (depletion of air in lungs) the frequency manifest deviation from what was expected. At high subglottal air pressure it is seen that the frequency increases and vice versa. The correlation between subglottal pressure and frequency shows a well-behaved functions and, therefore, it is safe to say that it has an influential effect on the voice frequency. It should be kept in mind that the subglottal pressure measurement itself was performed using an approximate method which at its best condition provide 93% accuracy. However, it is interesting that the subglottal pressure and measure frequency demonstrate such a good correlation.

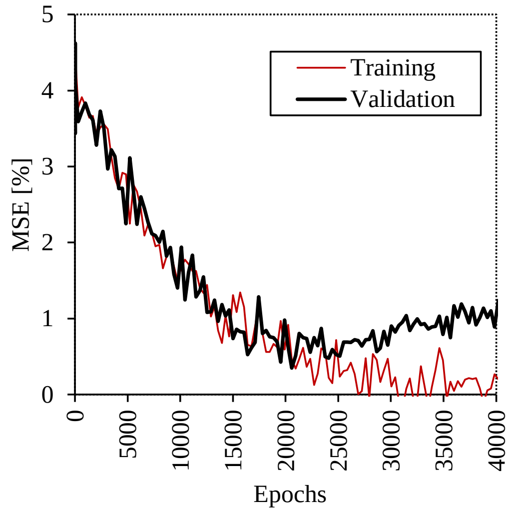


Fig. 6 Training and validation MSE for ANN

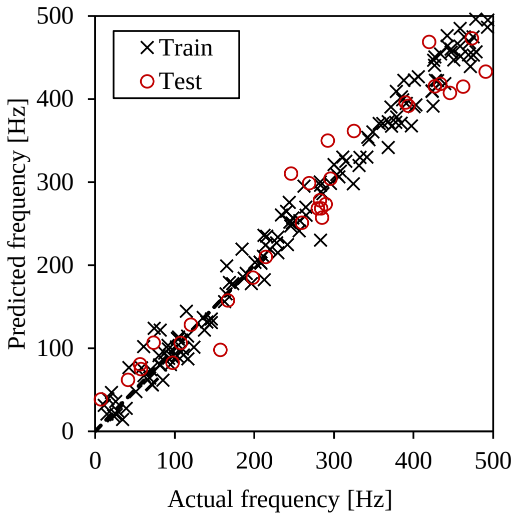


Fig. 7 Training and testing predicted value by ANN in comparison to measured value

5.2 ANN results

The data acquired form subglottal pressure estimation and frequency measurement was further used to train an ANN model for predicting frequency of voice. Preparing an ANN model includes three stages. At the first stage, the structure of the network should be determined, number of inputs and outputs and the hidden layers which was described above. The training process of the network accompanied validation of the model are performed simultaneously. Finally, the model must be tested before further utilization in the prediction of frequency from input data. For the present study, 60% of the data is selected for training, 20% for validation and the remaining for test of the ANN. The network is trained when the MSE value for validation deviate from MSE for training purpose. As depicted in Fig. 6, at iteration (epoch) around 22000 this deviation is appeared. Therefore, at this epoch the networks is saved and used for testing procedure.

6. Conclusions

In the present study, we aim to use nanotechnology sensors/actuators to capture pressure and frequency of voice singers and to send signals for improving subglottal breathing pressure. In this regard, a circular composite structure having 3 different layers are used. The core layer is nano-composite material reinforced with graphene nanoplatelets. The face sheets are piezo electric materials connected to electrical circuit capable of measuring and applying voltage to the piezoelectric layers. This sensors have extremely smaller size than conventional sensors attached to the neck of singer and, hence, minimizes the influences on the output voice of the singer. A brief theoretical framework are presented for nonlocal strain gradient theory and geometry of the sensor is described in detail. The controlling procedure along with experimental results on 10 professional singer participants are also presented. The results of the study indicate that the participants could gain benefit from the device for improving their ability in phonation and keeping their frequency at a constant level although they have difficulty in the beginning of the experiment getting used to the device:

- For most of the data collection periods the frequency were kept near D4 note equivalent to 277Hz for both men and women group.
- At high subglottal air pressure it is seen that the frequency increases and vice versa.
- The nano-sensor/actuators could be satisfactorily utilized in simultaneous measuring of subglottal air pressure and sending signal to singer for controlling breath pressure.
- The designed ANN model could be utilized in swift calculation for providing control signals.

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