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Design of Electrolarynx to Increase Energy Efficiency by Varying the Driving Source

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Abstract. The larynx is an organ in the human respiratory system that forms the basis of the speech production system. An electrolarynx is a device used by most laryngectomees to regain their verbal communication. Our objective was to design an electrolarynx with increased energy efficiency by modifying the driving source. Initially, we designed the electrolarynx to accommodate various driving signals. We then compared the voice output obtained by different input signals for quality and measured energy consumption using a digital multimeter. When compared to existing methods, the proposed driving source was found to be 11.1% more energy efficient. Voice quality was also better than the traditional driving source by 31.6%.

Keywords: Driving signal; Electrolarynx; Energy efficiency; Laryngectomee; Larynx; Speech

1. Introduction

Voice is a powerful mechanism to express ourselves. Voice production is an organized control of sensory and motor nervous systems (Simonyan and Horwitz, 2011). The cortical and subcortical areas of the brain control the speech production system. The lungs, larynx, vocal tract, and oral cavity are the main motor organs for speech production in human beings (Ackermann et al., 2014). The energy for producing speech originates from the lungs through the exhalation of breath. This vibrates the larynx and produces regular movement, resulting in laryngeal vibrations known as glottal waves (Bouchard et al., 2016). These periodic movements resonate, and intelligible speech is produced by the articulators in the oral cavity, such as the tongue, teeth, and lips (Visser, 2006).

A person loses his ability to speak when the larynx is removed surgically due to unavoidable circumstances, such as laryngeal cancer. The electrolarynx is an electro-mechanical device that acts as a larynx substitute. This device has an oscillator and a vibrator, which is held against the neck when the laryngectomee intends to speak. The vibrational energy passes through the neck surface, and speech is produced by proper articulator movement (Gironda and Fabus, 2011). Apart from laryngectomees, this device can also help patients who are critically ill and rely on artificial ventilation (Tuinman et al., 2015; Sato et al., 2016; Rose et al., 2018). The electrolarynx being a handheld device, one of the hands must be engaged in operating the device. This could prove awkward for laryngectomees as they socialize. Many researchers are working toward reducing the

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device's size to ease consumers' lives.

A wearable device has been designed that uses a thin vibrator on a plastic support attached to the neck region (Hashiba et al., 2007). This vibrator is controlled by a wireless controller kept in the user's pocket. Due to the required 9 v energy supply, this entire system is still substantial. The vibrator size reduction method was also employed in Madden et al. (2011), where the researchers designed an actuator for handsfree operation using a pager motor. However, pager motors' current handling capacity is very low at about 100 ma, meaning there is insufficient vibration at the neck region to produce audible speech, as sound level affects speech intelligibility (Knox and Anneberg, 1973; Weiss et al., 1979).

The recent work on electrolarynxes suggests a variation of fundamental frequencies to produce different tones for tonal languages (Guo et al., 2016; Ifukube, 2017; Wang et al., 2017a; Wang et al., 2017b). However, extensive training is required to produce pitch variations.

Control electronics designed using the electromyography activity of the neck muscles (Arifin et al., 2014; Fuchs et al., 2015; Oe et al., 2017) and video cameras to capture lip movement (Wu et al., 2013) provide an automatic control over the electrolarynx. A statistical method for varying fundamental frequencies suggests that, this allows for more natural speech (Tanaka et al., 2016; Tanaka et al., 2017). Based on the electrolarynx speech signals' feedback, the excitation signal is varied to accommodate differences in fundamental frequency. To decrease the electrolarynx's self-radiated noise, an interpolation of ultrasonic waves (Mills and Zara, 2014; Massey and Yilmaz, 2016) and time domain enhancement methods (Xiao et al., 2018) are used. The findings from Sardjono et al. (2009) and Coetzee et al. (2018) suggested that voices change due to advancing age after examining the mel-frequency cepstral coefficients, implying the possible changes in voice excitation sources. A simulated modified excitation source design revealed improved voice quality over conventional vibration methods (Madhushankara et al., 2017).

Being a battery-driven device, an electrolarynx's size should be as small as possible. However, battery technology is not advanced enough for new technology, so alternative energy-saving methods must also be accommodated (Madhushankara et al., 2015; Fuchs et al., 2016; Sofyan et al., 2016; Ejidokun et al., 2018). In our research, we designed an energy-efficient electrolarynx by modifying the driving source, thereby reducing battery size, which is proportional to battery capacity. We also employed li-ion batteries, which are commonly found in mobile phones due to their light weight and high energy capacity.

2. Methods

The following sections discuss our driving source and proposed electrolarynx designs.

2.1. Driving Source Design

The larynx's repetitive vibrations produce the volume velocity needed to form speech excitation signals (Stevens, 1996). Many mathematical models exist that are characterized as quasi-periodic, always null, or positive wave (Childers, 1995). Figure 1 represents the Rosenberg B model for glottal waves at a fundamental frequency of 100 Hz, with the open and return phases at a 3:7 ratio (Brookes, 2003).

to the laryngeal region due to the neck surface. To alleviate the neck surface region's complications, we pre-filtered the inverse of the neck transfer (N(s)) as indicated in Equation 1 (Meltzner et al., 2003):

$$N(s) = A \times \frac{(s-z)^2}{(s-p1)^2 * (s-p2)^2} \tag{1}$$

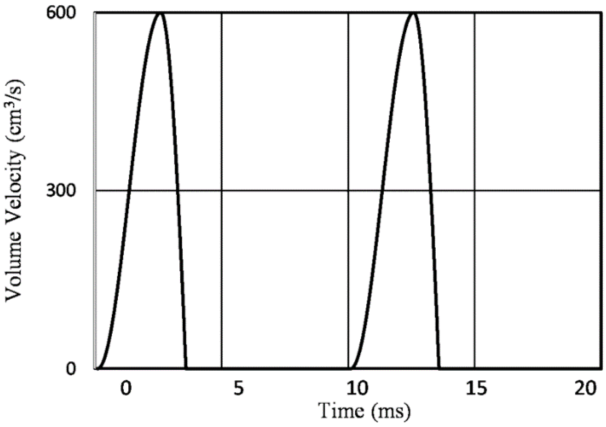

Figure 1 Glottal wave volume velocity

Here, A is the gain, z is the location of zero, and p1 and p2 are the pole locations. One study conducted on a normal adult male revealed that two zeroes are located at 120 Hz and two poles at 80 Hz and 1000 Hz (Meltzner et al., 2003). Using these values, the neck transfer function can be plotted as in Figure 2.

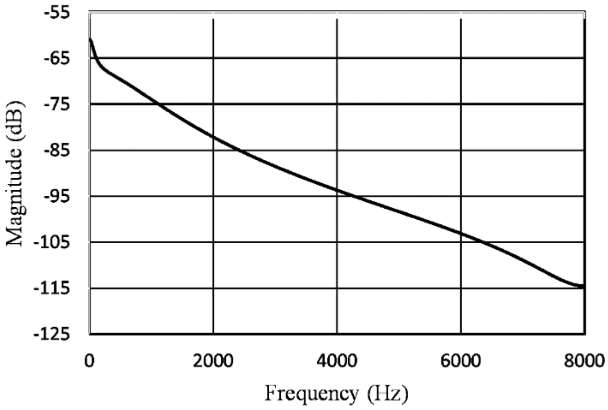

Figure 2 Neck transfer function of a normal adult male

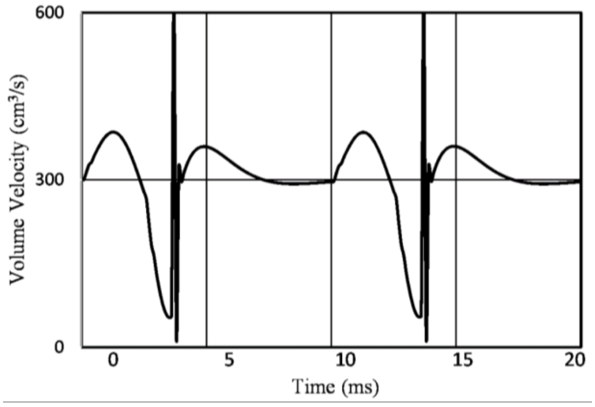

Figure 3 Designed modified glottal airflow for a normal adult male

We simulated driving source by filtering the glottal waves with the N(s) function using MATLAB and DSP System Toolbox Release 2014b (The MathWorks, Inc., Natick, Massachusetts, United States). Figure 3 represents a modified glottal wave for a normal adult male with a fundamental frequency of 100 Hz.

2.2. *Proposed Electrolarynx Design*

The block diagram of the proposed electrolarynx is shown in Figure 4. It contains a waveform generator, power amplifier, and transducer. The simulated waveforms are stored in the microcontroller's memory. The different waveforms' digital values can be stored in the memory as well to accommodate various driving signals. We utilized a digital to analog converter using a R-2R ladder network to obtain the waveform in a repeated pattern. A push-pull pair class B power amplifier was designed as an operational amplifier negative feedback loop (Boylestad et al., 2002).

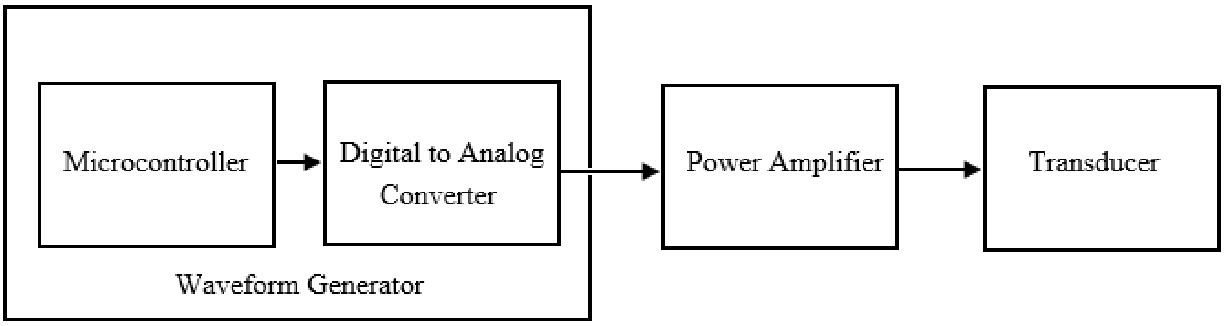

Figure 4 Electrolarynx block diagram

2.3. *Experimental Setup*

The experimental setup is shown in Figure 5. The waveform was stored in an Arduino microcontroller Atmega328P as a lookup table in binary format (Hugeng and Kurniawan, 2016). We programed the microcontroller to generate an analog signal at a frequency of 100 Hz. The amplified signal was then fed to a transducer and held against the user's neck.

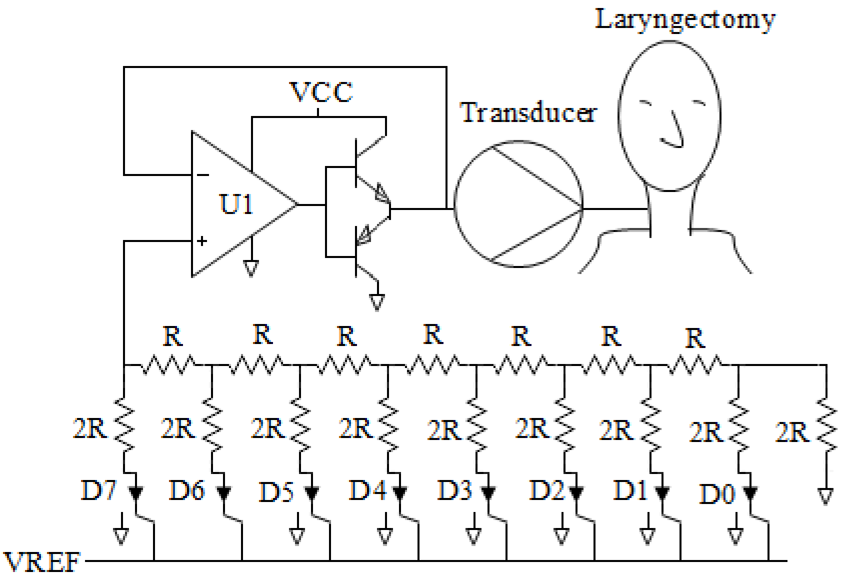

Figure 5 Experimental setup of the proposed electrolarynx's usage

3. Results and Discussion

We compared both the proposed source's energy efficiency and voice quality with that of a conventional electrolarynx: the Servox Digital Speech Aid. This device uses square waves with different duty cycles as the driving source. The persistent vowels from a normal adult male were recorded with the proposed driving source and square waves using a speech recorder, then digitized.

3.1. *Voltage, Current, and Power Measurement*

We connected two Li-ion batteries in a series to obtain the voltage (8 V) with no load condition. The system was continuously on until the series voltage reduced to 6 V, as measured with a digital multimeter. The current drawn was also measured using another multimeter in series with a circuit. Table 1 lists the current measurements with the various driving signals.

Table 1 Currents drawn by different methods

	Input Pattern			
	Square Wave (Duty Cycle)			Glottal Modified Wave
	(90%)	(85%)	(50%)	
Current (A)	0.36	0.35	0.26	0.32

The reduction in supply voltage was noted in 20-minute intervals and plotted accordingly (Figure 6). The product of the voltage and current is plotted in Figure 7 as the power consumed by the circuit.

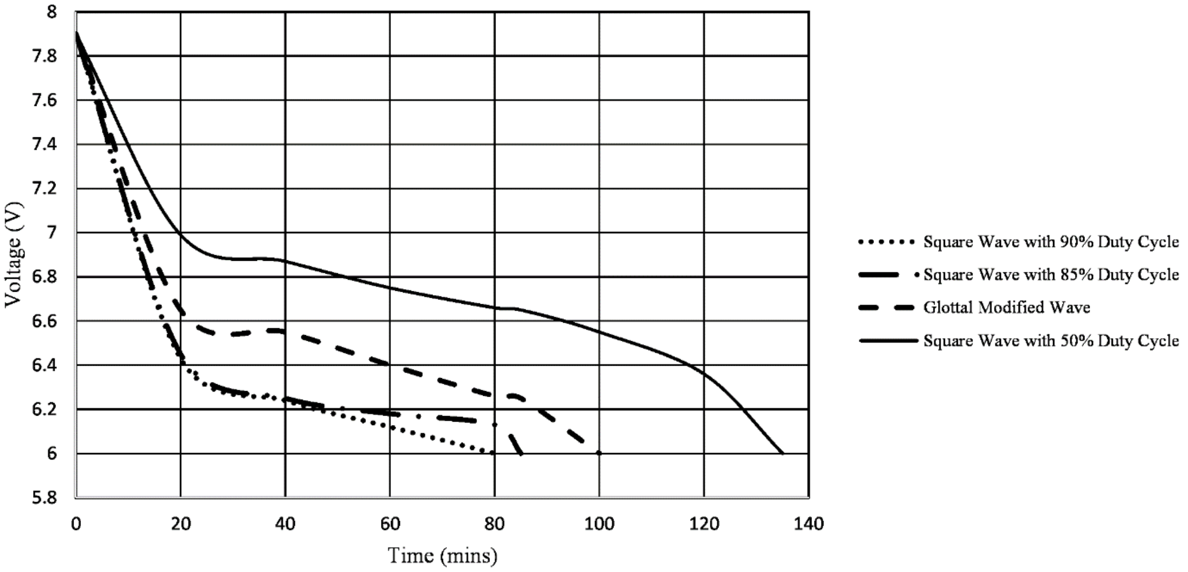

Figure 6 Power supply reduction

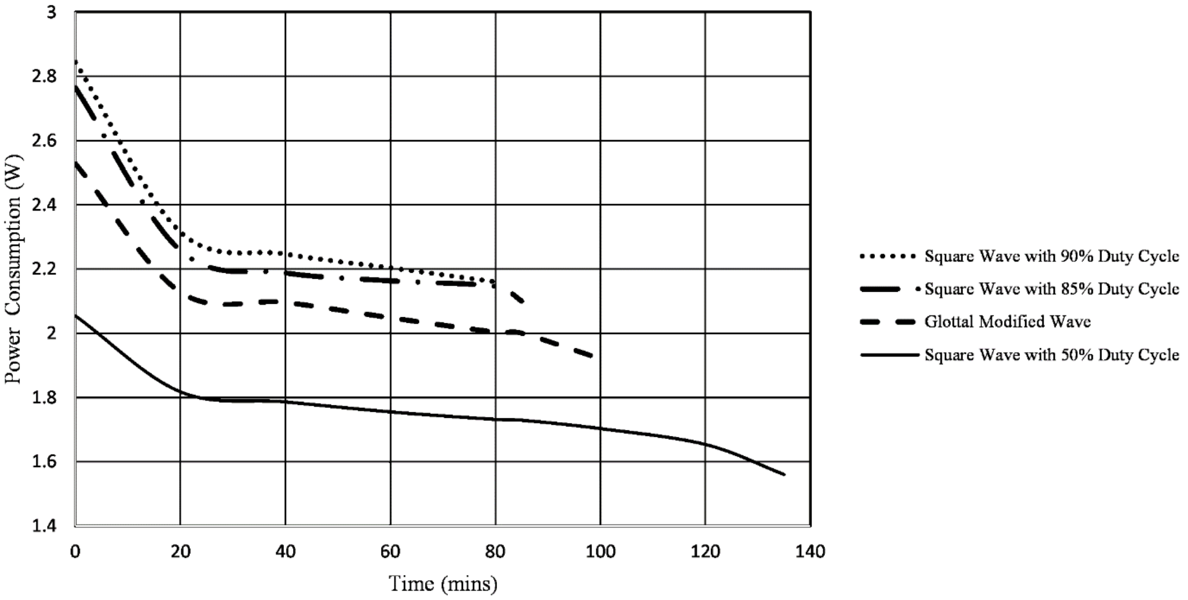

Figure 7 Power consumption

3.2. *Formants, Bandwidth, and Amplitude Measurement*

The volunteer, an adult male, uttered the vowels /i/, /a/, and /u/ in a soundproof room just as he would normally speak. Another three sets of the same vowels were recorded using the proposed electrolarynx, initially with the square waves (with different duty cycles) and then with the modified waves as the inputs. All vowels were recorded using the Voice Recorder application in a Motorola Moto G3 device and saved in the MPEG Audio Layer3 format. We performed a linear predictive coefficient analysis on the recordings using MATLAB with a coefficient of 12. We measured the distances between the formant frequencies as Euclidian distances after converting them to the Bark scale. The distance between the first two formants across the different types of vowel production are compared in Figure 8.

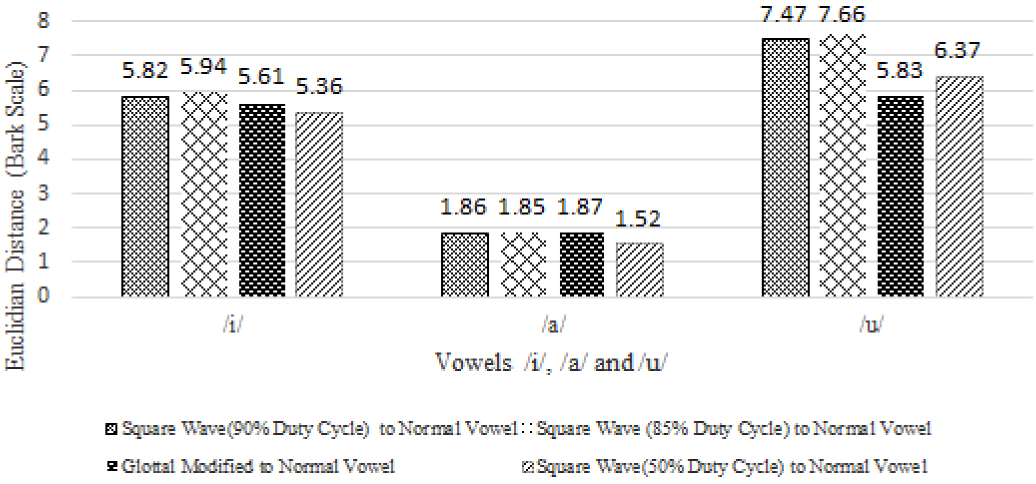

Figure 8 Average Euclidian distance of F1 and F2

Figure 9 represents the average of the first two formant amplitudes across various input sources.

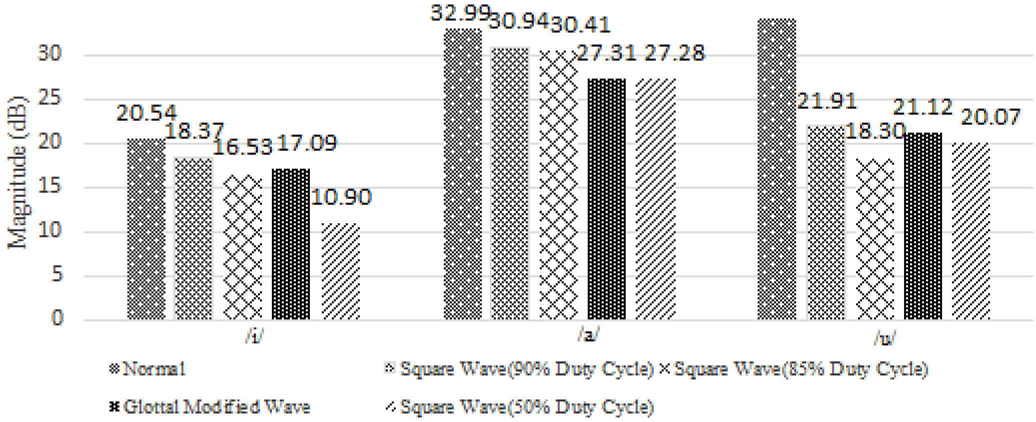

Figure 9 Amplitude plot of formants for vowel /i/, /a/, and /u/

An average of Fi/BWi for the first two formants is plotted as in Figure 10. Device leakage noise due to improper coupling of the electrolarynx to the neck surface was measured for all three methods and plotted (Figure 11).

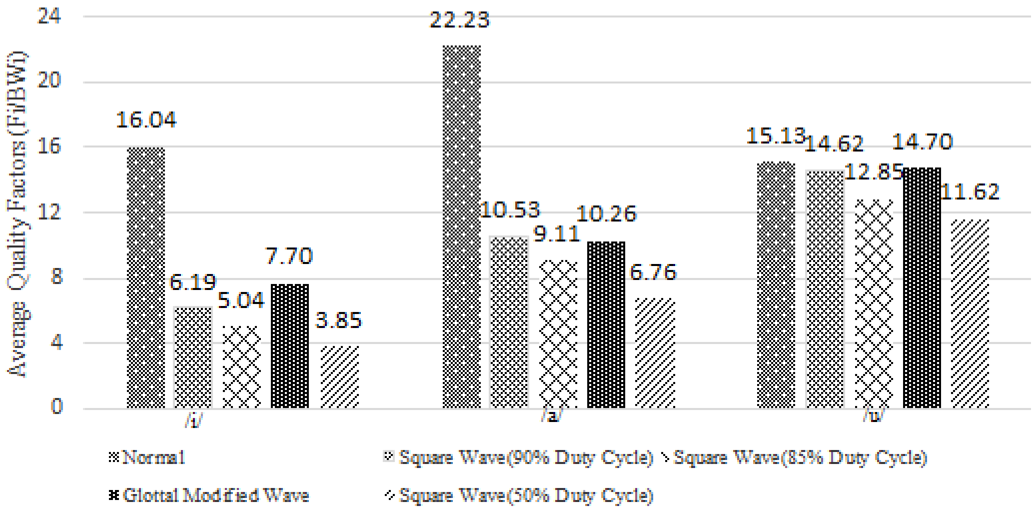

Figure 10 Average quality factors for /i/, /a/, and /u/

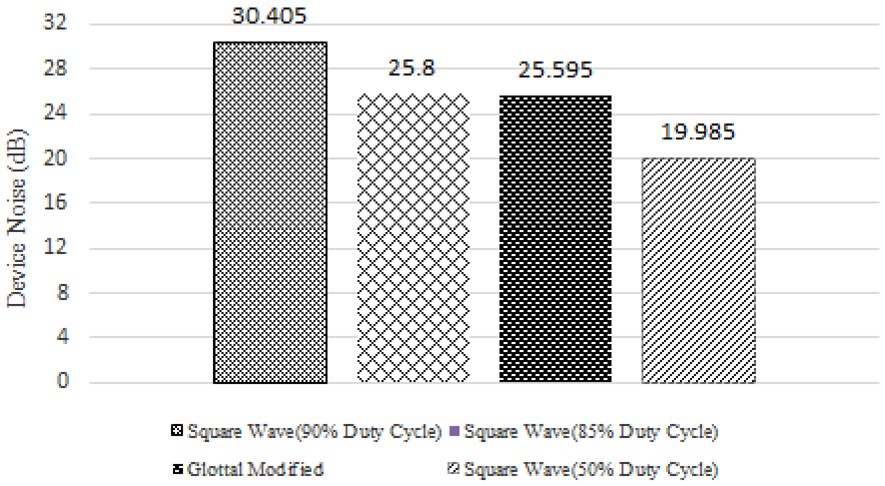

Figure 11 Device background noise with different driving sources

This work puts forward an alternative electrolarynx input signal that reduces the circuit's required energy. The features of this experiment are extracted from Figure 6 to Figure 11 and yielded the following observations.

When the proposed waveform is used as an input, the reduction in battery voltage improves over the square wave input at 90% and 85% duty cycles, respectively. The formants produced using the proposed waveform are nearer to normal vowels than those of the square waves in all three duty cycles, as indicated by the Euclidian distance. The peak amplitude from the proposed waveform is comparable to that of the square wave at 90% duty cycles. The signal generated when the device was powered with no lip movement (leakage noise) is less for the proposed wave when compared to the square waves at 90% and 85% duty cycles, respectively. The sound quality is highest when using the proposed wave at 31.6% duty cycles, which is more than that of the square waves at 50%. Therefore, a modified glottal wave betters vowel quality more than the square waves at all duty cycles, as 50% duty cycle waves consume less current. To perform the same task, the maximum energy efficiency of a modified glottal wave is 11.1% more than the square wave of a 90% duty cycle, as calculated from Table 1.

4. Conclusions

We have shown how an alternative electrolarynx driving signal leads to less power consumption and hence more energy efficiency with either improved or analogous performance in terms of formant distance, amplitude, quality factor, and leakage noise.

In addition, the present work was carried out using an Arduino Uno development platform, which consists of as many as 20 pin chips, along with other peripherals that are not required for the proposed electrolarynx. The design of an application-specific integrated circuit with fewer pins and constituents will lower the inactive current and further improve battery performance.

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