Development of a Variable Frequency Artificial Larynx and Some Behavioral Studies*

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Voice, the vehicle of speech and language, is the result of the interaction of the air flow from the lungs and the vibration of the vocal cords. However, there are some people whose larynx has been surgically removed because of the carcinoma of the larynx or for some other reason. If it may be said that speech is our most important characteristic, then it follows that the surgical removal of the larynx affects the most human part of us. Developing esophageal speech or teaching them to use artificial larynx are the two major methods of rehabilitation of these patients. Though both have merits and demerits of their own (see Jayaram, 1975 for a detailed discussion), the physiological and psychological conditions of the patients sometimes restrict the choice to just artificial larynx. The presently available artificial larynges have many limitations, the limited frequency range provided being the chief among them. For example, the best of the available artificial larynges, WE Type 5A (Luchsinger and Arnold, 1965) provides for a frequency range of only 100-200 Hz which is not sufficient to bring about the needed intonational changes in speech. Second, there is no provision for changing the output intensity of the device. Third, the intelligibility of the speech produced with this artificial larynx is very poor, mainly because of the constant buzzing of the transducer when the instrument is on. Lastly, there is the problem of costs, particularly in the Indian context. For these reasons, the development of a new artificial larynx which overcomes the above limitations is undertaken.

Design Objectives for an Artificial Larynx

Though no exhaustive survey of the opinions of postlaryngcctomised patients has been made so far to determine what would be an ideal artificial larynx, from the standpoint of achieving normal speech, the following attributes appear to be essential :

(a) For the speech to sound natural it should have pitch inflection and provision for a suitable fundamental frequency with harmonics. An artificial larynx should provide for a wide frequency range and which can be continuously changed. There should be a provision for selecting the optimum frequency of the individual because at this frequency, the vocal tract resonates. Accordingly, it was decided to design an artificial larynx which provides for a frequency range of 50 to 350 Hz (this range was decided following data from a study on inflection patterns in normal speech) from which a suitable fundamental frequency for each individual, with a rich supply of overtones to match his

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optimum, can be selected instantaneously. Another design objective was that the frequency spectrum of the tone of the artificial larynx voice should be almost similar to that of normal voice.

(b) Output volume should be sufficient for normal conversation and there must be facility to vary it like in normal speech to suit the situation. The output volume of WE Type 5A (70 to 75 dB at a distance of 3 feet) would be disadvantageous depending upon the background noise and the distance between the speaker and the listener. Accordingly, it was decided to provide a variable output range of 60 to 110 dB.

(c) The artificial lanryx should be inexpensive and have a low operating cost.

(d) Secondary to the above but still of great importance, the device should be reliable with simple, trouble free operation for long periods of time. Simplicity of operation is very desirable so that the subjects require only a minimum of training and get the psychological benefit of vocal communication at the earliest. In addition, the device should be as free as possible of mechanical difficulties necessitating service and repair.

(e) Other design objectives considered were (i) the device should be inconspicuous and hygienic. It should be unobtrusive, without visible wires, tubes or other appurtenances, (ii) the device should be small in size so that it impedes the patients little in the use of their hands. These design objectives have been discussed in some detail in Barney (1958).

Construction of a Variable Frequency Artificial Larynx

Sound Source and Circuit Design

In the present study, a sinusoidal wave was selected as the sound source. The sinusoidal wave consists of higher harmonics thus giving the quality of normal speech. The circuit diagram of the artificial larynx developed here is given in Figure 1.

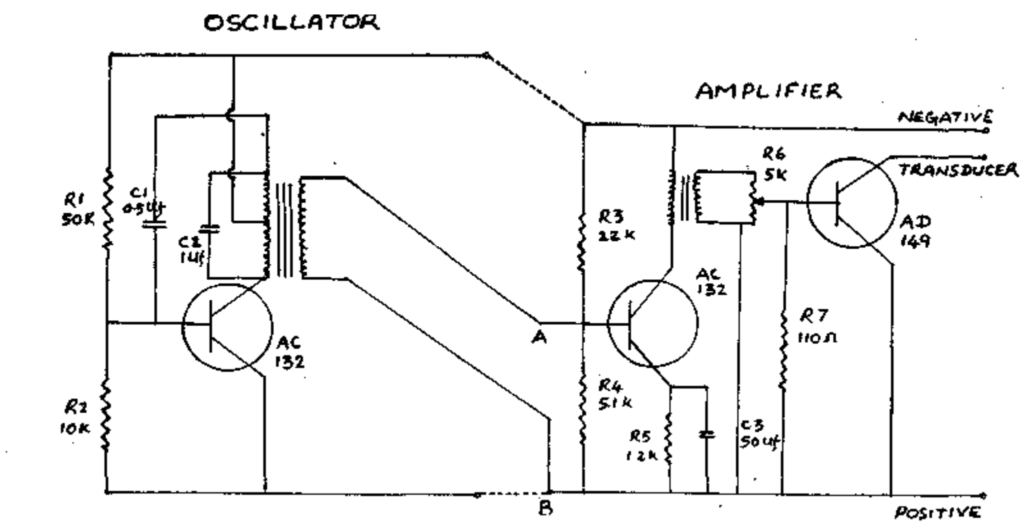

FIGURE 1

The variable frequency oscillator here consists of a simple Hartley oscillator which was preferred to a Weinsbridge Oscillator for three reasons :

(a) Non-availability of low voltage, low-current bulbs which act as negative feed-back elements in the Weinsbridge oscillator to control the amplitude of the oscillations.

(b) The output of the Weinsbridge oscillator is low and needs at least two or three stages of amplification to obtain enough signal strength to drive the amplifier. Since one of the design objectives here was to minimize both the cost and size of the artificial larynx, the Weinsbridge oscillator was rejected.

(c) A frequency range of 1 : 7 ratio can easily be obtained with a Hartley oscillator.

The frequency of oscillation is given by f = 1/2LC. Resistors Rl and R2 fix the operating point on the V — I characteristic of the transistor. Positive feedback is provided at the base of the transistor through the capacitor Cl. The tank circuit acts as the load in the collector circuit. The inductance for the tank circuit is provided by the primary winding of the transformer while a suitable capacitor C2 connected across the primary provides the necessary capacitance. The output of the oscillator is obtained from the secondary of the transformer. A power interruptor is introduced in the oscillator circuit.

The frequency range of the oscillator is from 50 to 350 Hz and is stable at discrete values. The output voltage of the oscillater varies from 1-9 to 2-1 volts. The variation is oly 0-2 volts over the entire frequency range and this small variation docs not bring about any large variation in the power output of the transducer.

A sinusoidal wave with higher harmonics is taken as the sound source here whereas in the WE Type 5A short periodic pulses from a relaxation oscillator were taken as sound source. The frequency variation is continuous in this artificial larynx but can also be fixed at any required value within this range. This enables us to select a fundamental frequency/optimum frequency for each subject. This is an advantage over the WE Type 5A artificial larynx.

The amplifier consists of two stages :

1. A single stage voltage amplifier using AC 132 transistor, and
2. A power amplifier using AD 149 transistor.

The operative point of AC 132 was fixed by means of R3 and R4. Necessary stability is obtained by using a suitable ratio of R3 and R4 of 4 : 1, The forward bias of the emitter section is provided by R5 and C3. The transformer is used as a load in the collector circuit. The input to the voltage amplifier is provided directly from the oscillator.

Frequency Analysis

The oscillator output at different frequencies was analyzed in the frequency bands 20-63 Hz, 63-200 Hz, 200-630 Hz, 630Hz-2K and 2K-6-3K. Frequency analysis was made in 10 Hz steps from 100 to 350 Hz. Analysis clearly indicated the presence of fundamental and harmonics in the respective frequency bands. Amplit ude of the harmonics was generally decreasing in the higher frequency bands and generally increasing in the low frequency bands (200 Hz-630 Hz, 630 Hz-2 K) for all input frequencies.

Transducer Characteristics

In the present study the transducer of the WE Type 5A artificial larynx was used as it was readily available. The constructors of this artificial larynx (Barney *et at.*, 1959) have taken into consideration the impedance of the throat muscles and tissues in the development of the transducer. This is important because the mechanical impedance of the throat muscles is 4000 times more than that of air and hence there will be difference in the performance of the transducer when pressed against the throat. Barney *et ah* (1959) have made a number of modifications in the HA1 receiver in order to give greater amplitude of vibration into the circuit. This transducer handles a power of 400 milliwatts and it also matches the impedance of the amplifier constructed here.

The Characteristics of the Transducer for a Pure Tone

To analyze the characteristic of a trans, ducer for a pure tone, a tone of 125 Hz was fed to the transducer at moderate power till the vibrator tone was heard. Analysis showed the presence of harmonics of uniform intensity upto 6K along with the fundamental of 125 Hz.

The characteristics of the transducer was analyzed in two other ways :

(1) The transducer's acoustical output with the original circuit of WE Type 5A was analyzed at the maximum and minimum position of the frequency control knob. At the minimum position, the analysis revealed that the components were weak in intensity over the fundamental and the fall in intensity in the higher frequency band was steep. At the maximum position of the frequency control, it was found that the harmonics were strong in intensity upto 6 K and the fall of intensity in the higher frequency band was not pronounced.

(2) The output of the transducer with the circuit developed here was analyzed for two tones of 125 and 150 Hz. The analysis revealed strong fundamental with rich components. Components were more and strong in the 1 K-4 K region. A comparison of the acoustical output of the transducer with the two circuits shows that the circuit developed here provides for a strong fundamental tone with rich and strong components whereas the circuit of the WE Type 5A gives very weak components.

The Characteristics of the Transducer for a Complex Tone

Frequency analysis of the normal voice when the subject phonated the vowel [a] at 125 Hz was carried out. The subject was instructed to phonate at this level keeping the intensity constant as far as possible. The tacho unit was used as an aid in maintaining the frequency level. Similarly, a tone of 125 Hz from the artificial larynx developed here was fed and resonated through the human vocal tract and a frequency analysis was carried out. Results of the comparison of the frequency analyses of these two tones are given in Table 1.

Table 1

Comparison of the tone spectrum of natural voice and the tone of the artificial laryHX developed. Table gives the frequency analysis of the vowel [a] phonated at 125 Hz

Frequency Bands	Fundamental of 125 Hz	
	Tone of the Artificial Larynx	Natural voice
63-200	125 Hz Fundamental Components. Components at 200 Hz	125 Hz Fundamental Rich Components
200-630	250 Hz—.Second Harmonic Components at 400 Hz	Second Harmonic at 250 Hz : Rich Components between 300-630 Hz with increasing intensity
630-2 K	5th Harmonic at 650 Hz 8th Harmonic at 1 K (Peak) Rich Components	Peak at 1 K. Rich Components upto 1-4K
2K-6-3 K	Components with decreasing intensity between 2 K and 5 K	Rich Components with decreasing intensity from 2-2 to 5 K.

Results from Table 1 show that the tone of the artificial larynx developed here has a closer proximity with the normal voice of 125 Hz. The observed harmonics and their amplitude were similar in both these. It can be said that the spectrum of the transducer tone is adequate as a source of harmonics for vowel production and that the tone of this artificial larynx has close resemblance to normal voice. This is a further proof of the naturalness of the tone of the artificial larynx developed here. This also lends support to the contention that the harmonics in the source spectrum of the normal voice are strong at low frequencies but drop in amplitude at the high frequencies. However, this has to be tested at other frequencies and also more extensively.

Amplifier Characteristics and Output Intensity

To measure the frequency and power characteristics of the amplifier, a constant voltage of 0-1 volt, for frequencies ranging from 50 Hz to 4 KHz, was fed as input to the amplifier. The gain control of the amplifier was placed little above the middle value. By feeding the output of the amplifier to AF Watt meter, power output of the amplifier was measured at different frequencies. The amplifier gives a flat frequency response from 250 to 700 Hz, with a little fall on frequencies below 150 Hz and above 1 K. However, the fall is not steep. From this it is clear that the observed harmonics were not because of the amplifier distortion.

The power consumption of the whole circuit was found to bft 560 milliwatts at the maximum intensity. The voltage drop was very minimal even after 15 minutes of usage. The voltage drop was found to be 0.1 volt which was ineffective in producing any change either in the oscillator output or in the amplifier in terms of power output or quality.

The output obtained from the secondary of the transformer of the voltage amplifier was fed to a 5 K Ohm logarithmic potentiometer and from here it was fed to the power amplifier. The potentiometer was calibrated with respect to the output of the transducer. The transducer output was measured at a distance of 1 foot both in free field and when pressed against the throat muscles. The output intensities of the artificial larynx in the two conditions are given in Table 2.

Table 2 shows that the output can be varied over a range of 39.5 dB in the free field condition and 33 dB in actual usage. The output range of the transducer when pressed against the throat muscles was 55 to 88.5 dB. The maximum intensity provided here is more than the peak intensity value employed by the normal speakers in their normal speech. Hyman (1955) puts the peak intensity value for normals at 79 dB. The wider intensity range provided here and the provision for varying it are the plus factors of this artificial larynx over the WE Type 5A which provides for a fixed intensity of 70 to 75 dB at a distance of 3 feet. It was also observed that the artificial larynx developed here transmits sufficient power to the pharyngeal region throughout the frequency region thereby facilitating the satisfactory development of the high amplitude region of the vowels.

Table 2

Output of the artificial larynx at a distance of 1 *foot under two conditions*

Frequency in **Hz**	Intensity (in dB's) at a distance of 1 foot			
	Free Field Condition		Transducer pressed against the throat	
	Min	Max.	Min.	Max.
50	70	104	56	85
100	72	104	56	84
150	74	107	58	88.5
200	74	108	58	88
250	72	109	58	88
300	77	109.5	55	86
350	73	109	55	84
Range	70	109.5	55	88.5

It has been indicated that the harmonics in the source spectrum of the natural voice are strongest at low frequencies dropping in amplitude toward high frequencies (Barney, 1958).

The device works on 9 volts D.C. The battery is sufficient to drive the circuit in its normal operation and for long durations. An off/on switch was provided between the battery and the instrument. From an analysis of the power consumption of the device, it was observed that the current drain through the whole circuit at the maximum intensity was 200 mA which is more when compared to the WE Type 5A artificial larynx (22 mA in the case of WE Type 5A). However, the power consumption of the device would be lessened to some extent by using the oscillator interruptor.

Mechanical Construction

The whole circuit was mounted within a rectangular tube .of 7 X 12 X3.5 cms. The tube has a circular head to house the transducer. The frequency variation knob was provided just below the transducer on the ventral side of the tube (when the instrument is in usage) in such a way that the subjects can operate this knob with their thumb. The frequency variation knob was calibrated using a frequency counter and a frequency range of 50 to 350 Hz was marked in steps of 25 Hz. On the dorsal side of the tube, the intensity variation knob was provided just below the transducer in such a way that the subjects can operate this knob with their forefinger. The intensity variation knob was calibrated based on the output of the transducer in the free field. An intensity range of 70 to 110 dB was marked in 10 dB steps. The frequency and intensity variation knobs can be glided horizontally and the arrangement was found to be functionally satisfactory. An oscillator interruptor was provided three centimetres below the intensity variation knob in such a way that it can be operated by either the ring finger or by the little ringer.

Behavioral Studies

Inflection Pattern in Normal Speech

The inflection pattern in normal speech was studied for two reasons :

(a) To decide about the frequency range to be provided in the artificial larynx to be developed, and

(b) To know the extent to which speakers can be trained to achieve the inflection pattern of normal speech with the artificial larynx developed here.

Five good speakers (those who use their optimum frequencies) served as subjects. The subjects were asked to read three sentences which were all marked for pitch levels. The frequency at the initial, medial and final position of the sentences were measured on the tacho unit as the subjects prolonged the vowels in these positions. The optimum pitch of these speakers were measured following Nataraja (1972). Good speakers were selected on the assumption that they will have good into national patterns. The results of this experiment are given in Table 3.

Only the highest and lowest frequencies were noted down. The optimum frequencies of the speakers were almost same (range 120 to 130 Hz). The variation in

Table 3

Speaking fundamental frequency as found in normal speech

Subjects	Sentence 1		Sentence 2		Sentence 3		Optimum Frequency
	Min.	Max.	Min.	Max.	Min.	Max.	
1	100	330	105	200	100	190	135
2	125	240	100	190	120	180	130
3	110	220	100	180	120	160	120
4	105	250	110	190	115	175	125
5	100	240	105	175	110	160	125

frequency shown by the speakers on different sentences was almost the same but for 5 to 10 Hz differences. This discrepancy might be due to the difference in their optimum pitch levels. The average variation from the level of the optimum pitch was found to be 20 to 30 Hz below the optimum and 120 Hz above the optimum frequency. In general, the maximum frequency achieved was 250 Hz though one speaker reached a high of 330 Hz. However, the intonation pattern and the 'meaning' conveyed by this speaker was in no way different from that of other speakers. A trained speech therapist observed for the possible differences in intonation.

The results of this experiment are contradictory to the findings of Barney *et al.* (1959) who found that a frequency range of 100 to 200 Hz is sufficient to duplicate the inflection pattern found in normal speech. Table 3 shows that the lowest and the highest frequency achieved were 100 and 330 Hz respectively. Since all the subjects selected in this study were good speakers who were assumed to have good intonation, it may be said that the speaking fundamental frequency may even be less than the above figures in the majority of the normal speakers. However, it was decided to provide for a frequency range of 50 to 350 Hz in the artificial larynx.

Training Normal Speakers in the Use of this Artificial Larynx

The five speakers included in the above experiment served as subjects for this experiment also. The speakers were explained the function and working of the artificial larynx developed here and the operation of the device was demonstrated to them. The speakers were asked to dramatize the sentences (the sentences were the same as the ones employed in the experiment described in the earlier section) using the present artificial larynx and making necessary variations from the level of the optimum (the frequency knob was set at the optimum pitch of each speaker). The speaking fundamental frequency was measured as in the previous experiment.. As Barney *et aj*. (1959) recommended the introduction of the tone into the pharyngeal cavity for good speech, the same procedure was followed here also.

Only normal speakers were employed in this experiment because of the non-availability of the laryngectomy patients. All the speakers who were trained in the usage of this instrument learned to speak with this instrument within 24 hours and one speaker took just 10 hours to achieve proficiency. The only difficulty the speakers faced was in achieving the frequency variation. Also, a little practice was required to find the proper pressure and placement of the transducer on the throat that yields the best results. The results of this experiment are shown in Table 4.

The results show that the speakers **could** achieve the frequency variation on **the** three sentences to the same extent found in normal speech (see Table 3 also). The speakers used the tacho unit as a visual clue in achieving the proper- frequency variation. The speakers in this study had no difficulty in using the oscillator interruptor and the intensity control. **The** results of this experiment indicated that the speakers could be easily trained to use this artificial larynx. However, this has to be tested with the laryngectomy patients also.

Intelligibility of Speech

Five good speakers who served as subjects in the earlier experiments spoke spontaneously for two minutes using the artificial larynx developed here. The output of the artificial larynx was kept at the middle value and the speakers made **the** necessary frequency variation from the

Table 4

Speaking fundamental frequency range on the three sentences achieved by the speckers ivith the present artificial larynx after training

Subjects	Sentence 1		Sentence 2		Sentence 3		Optimum Frequency
	Min.	Max.	Min.	Max.	Min.	Max.	
1	120	300	110	170	120	170	135
2	120	220	115	!80	135	175	130
3	125	180	120	175	110	155	120
4	110	230	125	175	100	150	125
5	140	190	130	160	120	140	125

level of their optimum frequency. All responses were recorded for further analysis. The recorded material was later given to four judges (two speech-language pathologists and two laymen) to rate the intelligibility of speech on a three-point rating scale of ' poor ', ' fair ' and ' good '. The judges were not told of any definite .criteria on which to judge, but were asked to judge the speech strictly from listener's point of view. However, they were asked to look for such factors as clarity, frequency variation, loudness, articulation, etc.

All the judges who evaluated the recorded speech indicated that the speech was intelligible. The judges considered 4 speakers to be 'good' and one subject ' fair ' on the speech intelligibility ratings. The subject whose speech intelligibility was 'fair' had good articulation but his frequency variation was not considered adequate by the judges. It was interesting to note that all the speakers who were proficient in the usage of the frequency variation knob were judged to have intelligible ('good') speech on the artificial larynx by the judges. However, the judges noted that all the speakers prolonged the speech to some extent.

These results support the findings of Barney *et al*. (1959) and Hyman (1955) who found that the speech of artificial larynx was always intelligible. Barney *et al* (1959) attributed the highintelligibility of the artificial larynx speech to the frequency structure of the transducer tone as well as to the introduction of the transducer tone into the pharyngeal cavity.

The good intelligibility of the artificial larynx speech observed in this study can be attributed to any one of the following factors or any combination of these :

(a) Frequency composition of the transducer tone.

(b) The speakers making frequency variation from the level of their respective optimum frequencies.

(c) The introduction of transducer tone into the pharyngeal cavity.

(d) All speakers had good articulation.

(e) The artificial larynx had sufficient output intensity.

(f) All the speakers prolonged the speech to some extent.

(g) One of the chief reasons for the poor intelligibility with other artificial larynges is the constant buzzing of the transducer during the non-articulation period. This constant buzzing of the transducer makes it difficult for the listeners to differentiate between syllables, words and phrases. In the present experiment, the speakers effectively used the oscillator interruptor thus eliminating the background buzzing during the non-articulation period.

Further Developments

The device should be tested on laryngectomees for intelligibility of speech as well as for their ability to effectively use this instrument. Further modifications are necessary to perfect this device. For example, (1) Square waves as the sound source give rich harmonics than the sine waves. This has to be attempted in future, (2) attempts must be made to develop an indigenous transducer, (3) power consump. tion of the device developed here should be minimised further and (4) miniaturisation of the device can be taken up.

Conclusions

A variable frequency artificial larynx has been developed. This artificial larynx has provision for changing the frequency from 50 to 350 Hz and intensity from 70 to 110 dB. A suitable fundamental for each individual, with a rich supply of overtones to match his optimum pitch, can be selected instantaneously with this device. The tone spectrum of this device is similar to that of normal speech. Wider frequency and intensity ranges provided in this artificial larynx are the new developments over the WE Type 5A artificial larynx. The intelligibility of the speech produced with this artificial larynx was considered to be very good. Introduction of the oscillator interruptor which could be the main reason for the improved intelligibility of speech with this device is another advantage of this device over the WE Type 5A artificial larynx. It has also been found here that the speakers can be easily trained to use this device.

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