CHOOSE-FOCUS-ANALYZE (CFA) EXERCISE

BT208 Transport Processes and Unit Operations

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Submitted by

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MOTIVATION:

I initially decided to work on a problem related to Heat Transfer Phenomena in Animals with adverse habitats. References and acceptable methods of modelling proved to be difficult and hence I decided on a shift of topic. For a considerable length of time, I studied a rather interesting problem – Modelling Traffic Flow as Fluid Motion. It was very interesting especially to get to know about the deep similarities and the striking relevance of laws of fluid dynamics when applied to traffic flow. There was a lot of reading done but I couldn't manage to narrow down a topic to work on. The traffic flow-fluid analogy has been well studied. So, I encountered difficulties in choosing a problem that is mathematically accessible yet one that has not been studied in considerable detail. Hence, I had to rather reluctantly abandon it, atleast for the present.

Hence, the present topic – *Vocal Folds – Their Functioning and Environmental Influences*. The practical implications, if exhaustively studied, are several. There are several hypotheses about musical output (the quality of singing and voice maintenance matter a lot to musicians) and its dependence on temperature. The motivation essentially came from observing contradictory advice for cultivating a good voice. The influence of temperature on voice has rarely been explored in detail, atleast to my knowledge. Further, an exact knowledge of the processes involved may also help in devising possible treatment techniques for people with voice defects or even with people whose voice is hampered to other underlying problems.

Though the present report makes several approximations, a reasonable qualitative picture can be built and lines of further work may be established to a considerable extent.

VOCAL FOLDS – THEIR FUNCTIONING AND ENVIRONMENTAL INFLUENCES

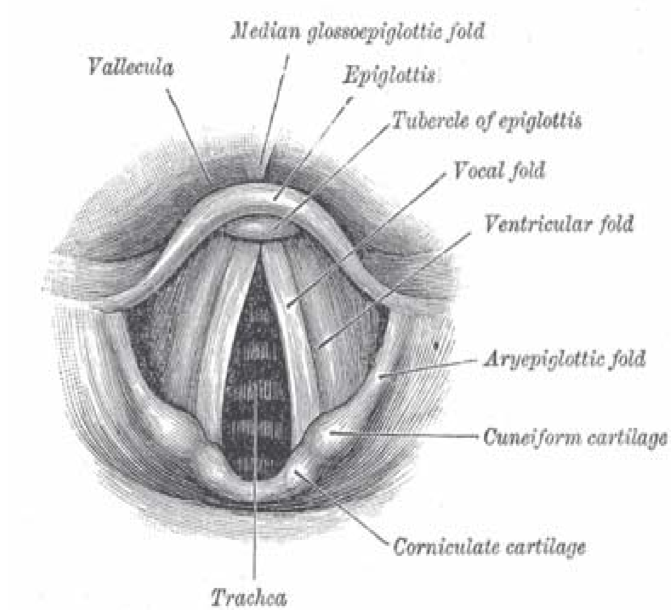
OBJECTIVE :

- To outline the mechanisms underlying voice production with a short calculation to have a feel of the numbers involved.
- To explore possible influences of temperature on vocal chords as a stand-alone organ.
- To suggest possible qualitative explanations for observed humidity effects on voice quality.

The actual numerical computations in the study of temperature influence on the vocal chords (with data being utilized extensively from acknowledged references) is my contribution in this exercise. Further, the short model calculation to illustrate the functioning of the chord is also essentially a self-carried-out exercise.

THE RELEVANT ANATOMY[1,2]:

The function of sound or voice production in humans is primarily performed by the vocal chords (the term 'vocal folds' is increasingly preferred and would be used henceforth in this report). The vocal folds are essentially soft tissues that are found at the top of the trachea. They are embedded and surrounded in thyroid cartilage and receive limited blood circulation, hence appearing white. They are seen as triangular membranes stretching horizontally across. The dimensions of the folds vary between males and females. The vocal folds serve as a gateway between the subglottal and supraglottal airways. The morphology has been described[3] conveniently by classifying the vocal folds into regions – a pliable, non contractile mucosal region called the *cover* and a muscular fibrous region called the *body*. The entire framework of the cartilage and the folds together with adjoining nerves is referred to as the larynx (or more commonly as the voice box). The larynx is positioned essentially at the point of separation of the pharynx into the trachea and the oesophagus, acting as a sort of valve.



Source : Wikipedia

THE MECHANISM OF SOUND PRODUCTION:

The lungs blow air against the vocal folds that are closed, but are more loosely held. Air pushes through the very small space between them called the glottis and in so doing, makes the covering of the vocal folds, known as the mucosa, vibrate. This occurs by means of a phenomenon known as the venturi effect. As air passes through a constricted passage, the velocity increases thereby creating a pressure drop. This draws in the mucosa from each vocal fold, which meet down the middle, only to be pushed aside by more air from the lungs. This cycle creates a repeating undulation which is known as the mucosal wave. The regularity of the mucosal wave results in a continuous and clear voice.

The elasticity of the mucosa depends on the integrity of the layer immediately beneath it, known as the superficial lamina propria, or Reinke’s layer. It is a special network of substances, unique in the body, that can support the stresses of vocal fold vibration over the long term.

The volume or amplitude of sound produced is a result of the pressure of the air that is blown past the vocal folds. A forceful expulsion of air from the lungs raises this pressure. Of course, the vocal folds must increase tension to maintain the near-closure that is needed for the venturi effect. If they do not, the increased air pressure will simply blow them aside and interrupt vibration. This tensing of the vocal folds usually happens instinctively, without conscious effort. Elasticity studies show that such tensile changes are freely permissible in the vocal fold.

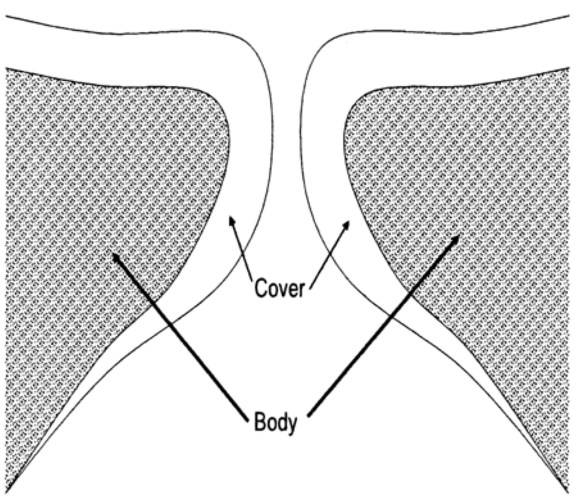
The frequency of the mucosal wave determines the pitch of the voice. The vocal folds are able to elongate and contract. This forms an important means of increasing vocal fold tension. Tension must be altered symmetrically in both the chords. A person performs this activity rapidly and throughout his lifetime.

A QUANTITATIVE PICTURE:

There is a pressure gradient between the subglottal and supraglottal regions which works to around 10 cm of water[4]. This arises in accordance with Bernoulli's principle whereby an increase in velocity is pronounced as a pressure fall. Typical velocity in the glottis can be taken to be around 50 - 75 m/s[5]. This would show the flow of air to be laminar as a computation of the Reynold's number yields

$$N_{Re} = \rho v D/\mu \quad < 2000$$

(ρ= 1.2 kg/m^3, D – the thickness of the glottis – typically[6] 0.12 cm, μ= 1.7 X 10^{-4})



Source : Reference 2

From the Venturi Equation, we have,

$\Delta P = \rho(v_2^2 - v_1^2)/2$, where v_1 and v_2 are the subglottal and glottal velocities respectively.

Making use of above values, we can estimate the sub glottal velocity v_1 to be around 29.4 m/s.

AN ANALYSIS OF TEMPERATURE INFLUENCE:

It is widely believed that a cold environment results in a poor voice. This hypothesis is now put to test. The study accounts for the temperature influence only on the vocal folds as a stand alone organ i.e., temperature could still influence other organs that have a role to play in voice production, like the lungs, and thus dictate the ultimate results in a different way. However, we examine the effects of temperature variations on the vocal folds as such.

Assume a laminar flow of air around the vocal folds (justified by the N_{Re} derived earlier). Let the temperature of the environment be 20°C while the folds are initially, essentially at the body temperature of 37°C. Let T be the temperature of the folds at any instant t. Assuming a heat transfer in accordance with Newton's law, we may write down the heat transfer equation as

$$dQ/dt = -hA(T-20)$$

Solving, making use of appropriate boundary conditions (T = 37°C at t = 0),

$$msdT/dt = -hA(T-20)$$

$$T = 20 + 17 \exp(-hAt/ms),\text{where}$$

h – heat transfer coefficient for the system ~20J/kgK

A – Area of vocal folds

M – mass of vocal folds

s – specific heat capacity of vocal folds ~ 4200 J/kgK

DIMENSIONS (from references[7]):

Vocal fold : (1.4 X 1.4 X 1) cm

Density : 1.043 g/cc

This yields $T = 27.5°C$ at $t = 30$ min.

So, $\Delta T = 9.5°C$.

Now, assuming expansion of vocal folds along one side (the other side being fixed to tissue),

$$\Delta L/L = \alpha \Delta T = (69 \text{ X } 10^{-6})(9.5)$$
$$= 0.000655$$

Young's Modulus of fold7 = 40.7 kPa

$$Y = \text{Thermal Stress/Strain} = T_{th}/(\Delta L/L)$$

yielding T_{th} i.e., additional tension = 0.00523 N.

For producing a note of frequency f = 256 Hz, say, Tension required (Ti)= 7.52N ($f = (1/2l)\sqrt{(T/m)}$).

Due to an increase in tension, the altered frequency $f' = f \sqrt{[1 + (Tth/Ti)]} = 256.1$ Hz.

Thus, it is clear that temperature variations do not show a significant influence on frequency response of vocal folds, when the latter is treated as a stand alone organ. We could therefore infer that temperature variations, causing a degradation in voice, do so by a different mechanism. They have little influence on the vocal chord as such.

Though approximations have been made at several stages during calculations in a qualititative fashion, the measurements used have been taken from authentic sources. The qualitative approximations nevertheless serve to make an assertion, that no direct influence of temperature on vocal folds is observable. The ultimate effect on voice quality depends on several other factors, which are not looked into in this report.

AN OUTLINE OF HUMIDITY EFFECTS:

The humidity (relative) of inhaled air has been known to influence voice quality and induce perturbation changes in the voice. Experiments carried out indicate that a low humidity of about 30% induces significant perturbation in voice – both in loudness and frequency. However, a high humidity fails to show any appreciable increase in perturbation levels, atleast for short provocation periods.

Hemler et al[8] suggest that there exists a critical humidity beyond which perturbation increases are negligible. However, no experimental estimate has been obtained for such a critical value.

A possible interpretation could be on the lines of high humidity air, being rich in water vapour, to an extent compensates for perturbation by lubricating the vocal folds. Lubrication of the vocal folds is commonly practiced among professional singers by ingesting water at room temperature.

FURTHER WORK:

Possible further work can focus on

- An exact treatment of air flow through the glottis. Infact, the glottal area itself changes and could be looked at as an orifice with varying area and suitable quantitative estimations of air velocities and pressure drops could be made.

- A more generalized analysis of temperature influence which would examine the 'net' effect of temperature on voice production.

- A quantification for the humidity effects on voice perturbations.

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