On the acoustics of spread lips

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Abstract
In response to our incomplete understanding of how the 3-D geometry of the lips should be modeled in 2-D area functions, we present some measurements made on simplified physical models of the vocal tract. Our main result is that it is possible to match the formant pattern of a notched tube with that of an unnotched tube provided that an increment is added to the length of the unnotched tube. This increment was found to vary systematically with the depth of the notch and, to some extent, also with the size of the tube's cross-sectional area. We expect these results to be relevant to representing articulations with the mouth corner posterior to the midsagittal anteriormost point of the vocal tract - as in spread vowels, especially when emphatically and emotionally spoken.

Determining the VT area function for spread lips

In the acoustic theory of speech production the shape of the vocal tract (VT) is represented as a series of uniform cylindrical tubes, the so-called area function. The cross-sectional areas along the tract can be accurately predicted from information from 2-D lateral profile images of the midsagittal contours of the VT (Heinz & Stevens 1965, Sundberg et al 1987, Ericsdotter 2005).

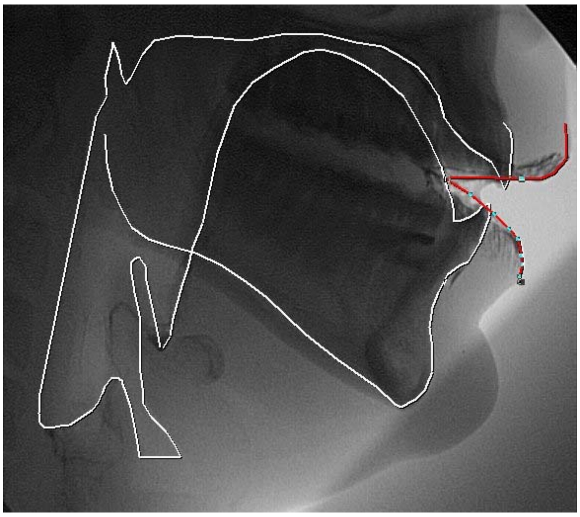

Figure 1. How do we determine the length and area of the lip section from an articulatory profile? What is the effect of the mouth corner on the formant pattern?

While this method works well for the pharynx and the oral region, it is more difficult to apply to labial articulations. Standard theory represents the lips in terms of a single section having a certain length and opening area (Fant 1960). The problem addressed in this paper is the mapping of the 3-D geometry of the lips onto these two parameters (Figure 1).

To shed some light on this topic we made acoustic measurements of two types of physical models: (i) A set of specially designed cylindrical pipes; (ii) a hybrid device, here referred to as HACMOD, whose front end is a 3-D replica of the anterior portion of the VT and whose posterior part consists of a pile of circular plexiglass washers with centered axial holes.

This is work in progress. The cylinder measurements are the primary focus of this report. We expect to have more to say on HACMOD at the time of the meeting.

Cylindical tubes with & without notches

Our first investigation involved measuring the resonance characteristics of cylindrical cupper tubes with uniform cross-sectional areas. Three diameters were selected: 20, 28, 35 mm. This project was undertaken to provide baseline data for the more complex task of analyzing the acoustic properties of HACMOD.

Figure 2 illustrates the design of these tubes. "Lip openings" and "mouth corners" were simulated by cutting and filing the tubes at one end so as to produce wedge-like notches. Use of paper templates glued to the tubes improved the precision of this procedure. The center columns of Figure 2 illustrate their geometry. The depth of the notches was varied between 0, 1, 2, 3, 4, and 5 cm. In the side view they produce straight lines; from the top or the bottom their contours produce a parabolic projection.

Tubes without notches were ‘long’ and ‘short’. Short tubes ended at the mouth corner; Long tubes extended from source to the top edge.

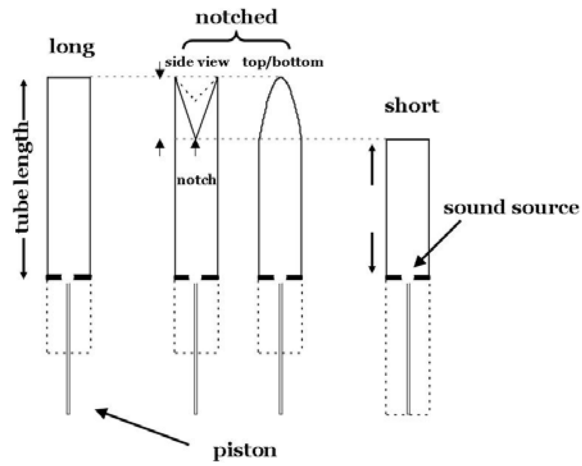

Figure 2. Cylindrical tubes used to study “spread lip” configurations.

The formant frequencies of these resonators were measured by means of a manual frequency search. The sound source was the STL ionophone (Fransson & Jansson 1971) whose sine-wave output was varied in frequency to identify the resonance peaks. It was mounted on a tight fitting piston whose position in the tube could be continuously varied. Special care was taken to achieve an airtight seal between the ionophone rod and the tube. A microphone attached to an oscilloscope was mounted close to the open end of the tube.

As a plasma is generated between the ionophone electrodes, heat is dissipated. The temperature of the air inside the tube was continuously monitored by two thermocouples, one placed near the tube opening; the other was inserted through the piston at 2 cm above the source, off-center. During a given session the average temperature inside the tube was about 30° C. To keep temperatures steady, air circulation was achieved by having a fan inject a laminar air stream into the tube.

Cylindrical tube data

The data set for the measurements were as follows:

Overall tube lengths: 12 – 21 cm;

Notch depths: 1, 2, 3, 4, 5 cm;

For every notch depth, measurements were also made of two tubes without the notch: The full tube length (column 1 in Figure 2) and the short tube (column 4 in Figure 2).

Figure 3 presents the plot format used to analyze the data. The temperatures recorded during the experiments were used to adjust all the frequency measurements so as to reflect a temperature of 35° C inside the tube.

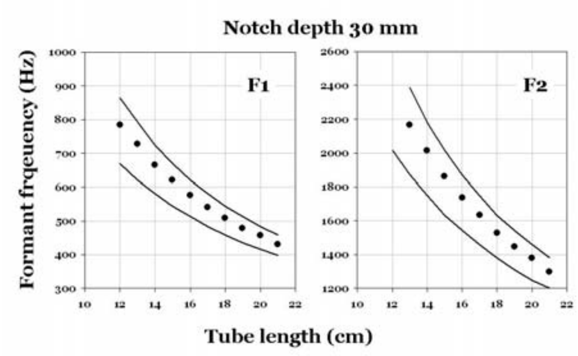

Figure 3. F1 and F2 measurements plotted against total tube length. Notch = 3 cm. The top line represents the formant value for the short tube [bottom-to-mouth corner]; The lower curve pertains to a full-length tube without a notch. The diagram describes the results for a temperature of 35° C inside the tube.

All formants presented patterns similar to those of Figure 3 regardless of the geometric parameter values. Without exception the data for the notch conditions fell inside the margins set by the ‘long’ and ‘short’ tubes (columns 1 & 4 in Figure 2).

It can be seen that F2:s data point for the 12 cm notched tube is missing in Figure 3. This is the case because at higher frequencies a resonance (usually F4, sometimes F3 and F2) would often exhibit a low Q value. Making an estimate of the peak in those cases was considered unreliable.

Modeling the measured values

Acoustic theory enables us to predict what the values for the tubes without notches ought to be. This provides us with an opportunity to check on the numerical accuracy of the measurements.

Since the unnotched tubes have uniform cross-sectional areas, their resonance frequency would be expected to be given by:

$$f_n=(2n-1)*c/(4*(l+l_{eff})) \quad (1)$$

where n is formant number, c speed of sound and l_{eff} is the effective length of the pipe.

At 35° C the speed of sound in cm/sec is:

$$c= 33145*SQRT(1+35/273.16) \quad (2)$$

We should note that the effective length of a pipe that is unflanged is different from the end correction used in VT calculations (Fant 1960:36). It is given by

$$l_{eff} = l + 0.6*r \quad (3)$$

where r is the cylinder radius (Kinsler et al 2000:274).

The measurements were found to deviate by less than 1.3 % from the calculated values.

Equivalent lengths for notched tubes

In analyzing the results for the notch condition we compared the observations with a set of equivalent unnotched tubes. We asked: Is it possible to equate the acoustic properties of a given notched tube with those of an unnotched tube whose length is chosen so as to match the unnotched formant pattern?

For each measured formant value we calculated the following number:

$$l_{inc} = (35204/(4*f_{obs})) - (l_{short} + 0.6*r) \quad (4)$$

where 35204 is the speed of sound at 35° C, f_{obs} is the measured formant value, l_{short} is defined as the distance between the bottom end and the "mouth corner" of the notch. The assumption underlying the formula is that the notch will add an increment (l_{inc}) to the length of the unnotched tube (l_{short} + $0.6*r$).

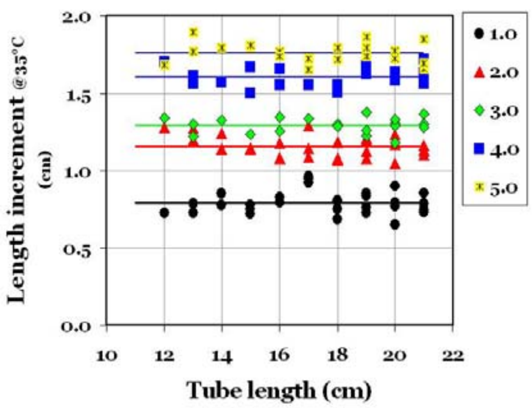

*Figure 4. Comparing the effect of notch depth in terms of the increment in length defined in Eq 4. When this increment is added to an unnotched tube whose effective length is [l_{short} + 0.6*r] a perfect match is obtained with the formant frequency observed for the notched condition.*

An example of how the length increments pattern is presented in Figure 4. It shows the effect on the length increment (l_{inc}) in a tube whose total length is plotted on the abscissa and whose radius is 1.4 cm. The notch depths (1 – 5 cm) are color-coded as shown on the right. Accordingly each colored cluster refers to a given notch depth. A positive finding is that formant number does not affect the increment much. Thus, formant measurements for individual conditions are pooled. The mean value of each cluster is indicated by a horizontal line.

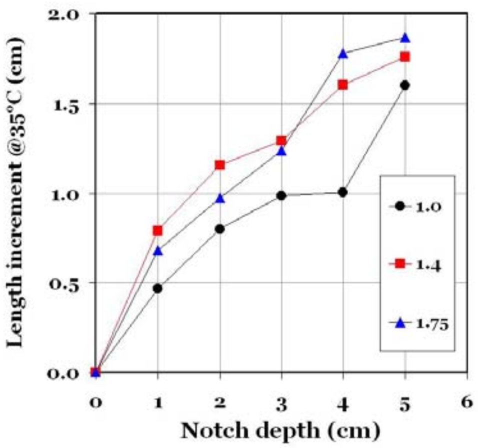

Figure 5. Summary of the data on cylindrical tubes with notches. The diagram shows the relationship between length increment, notch depth and tube radius.

As the size of the notch increases the increment gets longer. A similar result was obtained for the other two cross-sectional areas. In Figure 5 the length increment is plotted against the size of the notch with the radius of the tubes as parameter (r=*1.0*, *1.4* and *1.75*). For all cross-sectional areas the length increment increases with notch depth. Also to some extent the increment depends on tube radius. However the limitations of our method do not permit us to establish this trend with certainty.

Can the formant patterns of notched tubes be described in terms of unnotched tubes of equivalent lengths? In conclusion, it would seem that we can give an affirmative answer to that question.

A 3-D replica

To study the acoustics of the lips one would ideally like to have a physical model of the vocal tract capable of generating a realistic representation of pharyngeal and oral cavities and allowing, at the same time, the experimenter to observe the acoustic consequences of systematic manipulations of the geometry of the lips.

In partial attainment of this goal we developed HACMOD. This tool is a hybrid device combining the use of plexiglass washers (as in ACMOD (Sundberg et al 1992)) with a 3-D replica of the front part of the vocal tract (Figure 6).

The replica was constructed by first making impressions and casts of a human subject's anterior oral anatomy. From these casts, acrylic models of the jaws were produced. These components are presented in the foreground of Figure 6.

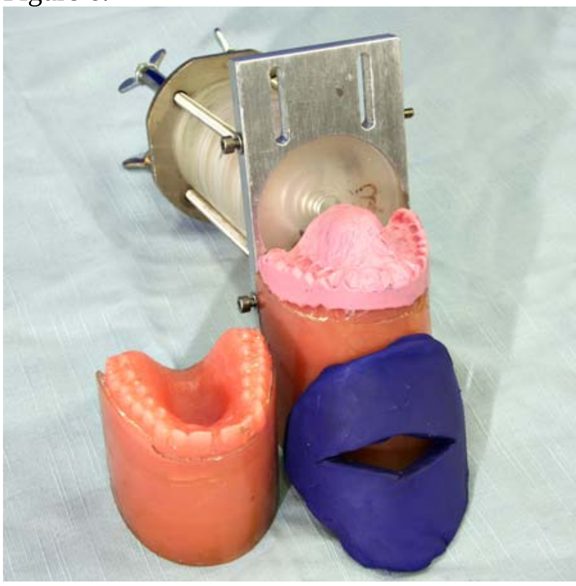

Figure 6. Components of the HACMOD replica of the vocal tract.: models of upper and lower teeth/jaws, lips, tongue shape and the posterior plexiglass unit.

On the left: the maxilla with the upper teeth and hard palate which is fastened to the metal plate and whose vertical position can be adjusted along the slits to simulate variations in jaw opening. A tongue made of lab putty is fitted into the mandibular component. A lip configuration is also shown. In the background: a glimpse of HACMOD's posterior region with the pile of 0.5 cm circular plexiglass washers with variable axial holes.

Figure 7 demonstrates HACMOD in assembled form.

Acknowledgements

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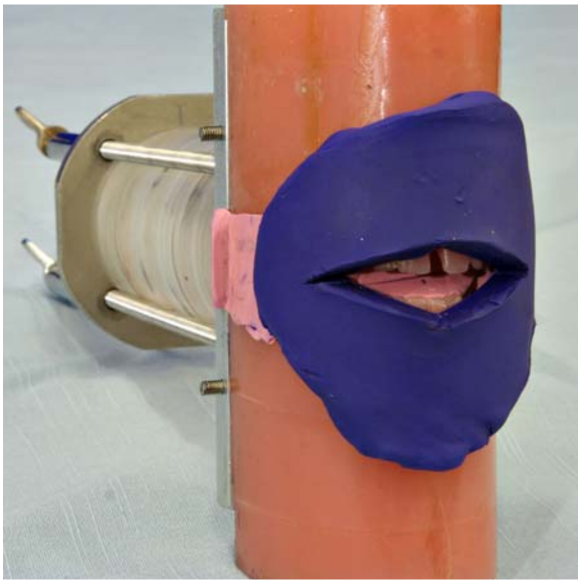

Figure7. The HACMOD components assembled.

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