Qualitative Theory of Formant Values

Linguistics 520: Introduction to Phonetics

In our first lab exercise, we learned that acoustic resonances are associated with standing waves, arising because of the interaction of sound waves with their reflections in enclosed areas. We also learned that even though it is quite complicated in general to calculate what the resonances of a particular structure should be, there are certain cases where simple reasoning leads to an accurate answer.

One such case is a uniform tube, significantly longer than it is wide, and closed at one end while open at the other. If we restrict our attention to frequencies substantially below those whose wavelength is (twice) the radius of the tube, then we need to consider only the standing waves parallel to the long axis of the tube. These longitudinal standing waves will be perfectly sinusoidal in shape, since the tube is uniform in cross-section. They will have a (velocity) node at the closed end (since the particles immediately adjacent to the boundary are not free to move). Equivalently, there will be a pressure antinode at the closed end, since the hard boundary permits the pressure to vary. At the open end, there will be a velocity antinode (since the opening permits the air to move freely back and forth), or equivalently, a pressure node (since there is nothing for the pressure to "push against").

There are infinitely many sinusoids consistent with these boundary conditions in a tube of length L, having wavelengths $4L/1, 4L/3, 4L/5, ...$, and frequencies $C/4L, 3C/4L, 5C/4L, ...$. We measured the speed of sound in air, to a reasonable degree of approximation, by a calculation based on the frequencies of sounds produced by blowing across the open end of tubes of various lengths.

Fig. 1 shows the (particle velocity) standing waves for the first three resonances of a uniform tube open at one end and closed at the other. The two sinusoids plotted for each resonance show the minimum and maximum values at each point in the tube. A velocity node occurs where the curves cross in the middle of the tube. A velocity antinode occurs where the curves are maximally separated. Recall that pressure nodes correspond to velocity antinodes, and pressure antinodes correspond to velocity nodes.

This model is constructed with reference to a uniform tube, such as the pieces of plastic pipe that we used in the lab exercise, and is already a somewhat idealized version of such tubes. It also roughly corresponds to the the human vocal tract in a neutral configuration. In such a configuration, the width of the tube is roughly uniform along its length, and the length is large relative to the width. The fact that the tract is bent in the middle doesn't matter, any more than the coils of a French Horn do. Since a typical human vocal tract is about 17 centimeters long, and the speed of sound in air at room temperature is about 343 m/sec, this simple model tells us that the first three resonances will be at about $343/(4*.17)$, $(3*343)/(4*.17)$, $(5*343)/(4*.17)$, or about 500, 1500, 2500 Hz. If you plot this on an average adult formant space, you will see that it corresponds to a mid central vowel: F1 corresponds to vowel height, and 500 Hz. is neither high nor low; F2 corresponds to vowel frontness, and 1500 Hz. is neither front nor back.

Following this idea, in Figure 1 the closed end of the tube is fancifully named "LARYNX," while the open end is labelled "LIPS" with equal poetic license. In this way of thinking, the middle of the tube corresponds very roughly to the uvula.

This gives us a sense of where formants come from, but by itself it is not very useful in reasoning about the relationship between articulation and sound. Most vowels are not mid central, and no consonants are (since consonants by their nature involve a constriction). In general, the relationship between articulator position and resonance structure, even for a very simple one-dimensional model like the one we are talking about, requires a difficult calculation to determine exactly. Computer programs can do such calculations easily, as we will see later on in the course.

However there is a sort of "rule of thumb" that we can use to reason qualitatively, but accurately, about the effect of constrictions or expansions at various points in the vocal tract.

> **Rule of Thumb:** Constriction at a velocity node of a standing wave raises the frequency of this standing wave. Expansion at a velocity node lowers the corresponding frequency.
>
> Constriction at a velocity antinode of a standing lowers the frequency of this standing wave. Expansion at a velocity antinode raises the corresponding frequency.

Since the effect of constriction is always opposite to that of expansion, and the effect at a node is always opposite to that at an antinode, you just have to remember one clause of this rule correctly in order to get the other ones. One way to do this is to keep in mind that a constriction at the lips lowers all formants; and the lips are a velocity antinode for all standing waves; thus CONSTRICTION at a velocity ANTINODE LOWERS the frequency.

In between a node and an antinode, the magnitude as well the sign of the effect varies smoothly. Thus a constriction near an antinode will lower the standing-wave frequency, but by a little less than one exactly at the antinode; a constriction near a node will raise it, but by a little less than one exactly at the node; and half-way in between the node and the antinode, there is a spot where a constriction will leave the frequency of the corresponding standing wave unchanged. A constriction or expansion that covers node and antinode regions equally will have no effect.

In Figure 1, we have marked the (velocity standing wave) nodes with an "N" underneath each standing wave, and the antinodes with an "A," numbering them in each case from the front of the tract to the rear. Above each standing wave, we have marked the nodes with a "+", the antinodes with a "-", and the in-between points with a "0", to indicate the effects of a constriction. The effects of an expansion will be opposite, as noted.

Several useful general conclusions can be drawn, for example:

1. Since all the standing waves have a velocity antinode at the lips, a labial constriction will cause all resonances to fall.
2. Opening and closing the jaw, with no other articulatory change, tends to open and close the front half of the vocal tract somewhat more than the back half. Therefore such motion will raise and lower F1, which has only an antinode at the far front of the tract, and a node at the far back, while having little consistent effect on higher formants (which have both nodes and antinodes in each half of the tract).
3. Moving the tongue forward in the mouth will tend to cause a constriction around the F2 node labelled "N2", and an expansion around the F2 antinode labelled "A1," thus raising F2. Moving the tongue backward in the mouth will have the opposite effect.
4. A contriction slightly anterior to the F3 antinode labelled "A2" and slightly posterior to the F2 node labelled "N2" will lower F3 while raising F2. This effect is seen in many velar consonants, and is colloquially known as the *velar pinch*.

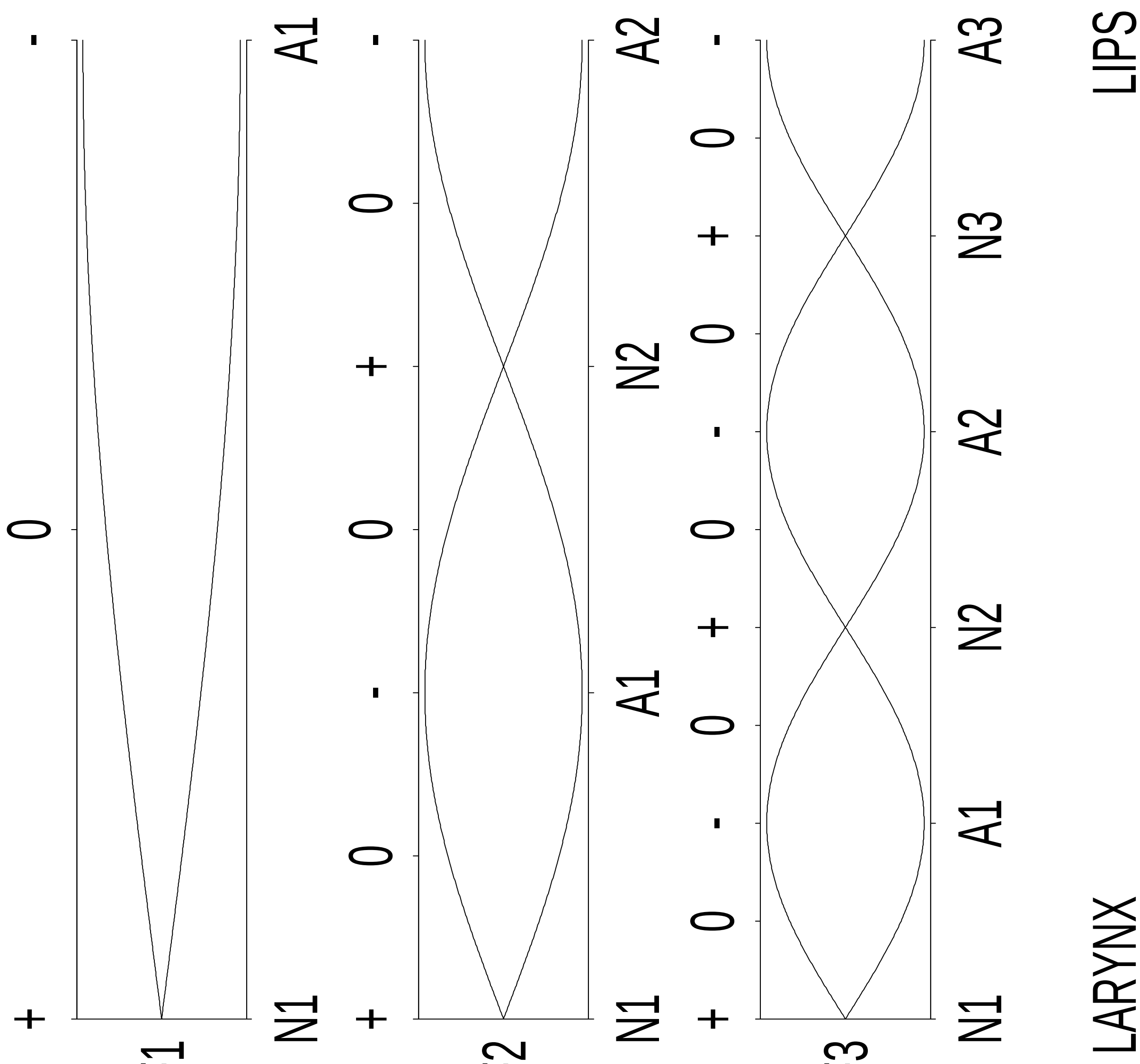

Figure 1: (Velocity) Standing Waves for Three Formants