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Physical models of the human vocal tract as tools for education in acoustics

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Abstract: We recently replicated Chiba and Kajiyama's physical models of the human vocal tract and found that they are extremely effective as manipulative tools for education in acoustics. This study overviews our previous development of the models and their application for education. The models we developed simulate the configuration of the vocal tract, and are of two major types: cylinder and plate. The interior, bottle shape of the cylindrical models was based on Chiba and Kajiyama's original measurements. The diameters of the holes in the 10-17 moveable plates of the plate-type model were also based on Chiba and Kajiyama's measurements, but the radius curves were approximated at 10 mm resolution in a step-wise fashion. We also developed a nasalized model, which consists of a side branch attaching to the cylindrical model. Our experience confirmed that when used in a classroom environment, the models increase student understanding of the acoustic theory of speech production.

1. Introduction

Chiba and Kajiyama (1941) made mechanical models of the human vocal cavity based on their cross-sectional measurements and confirmed that vowel quality is governed by the overall shape of the vocal cavity. Arai (2001) replicated Chiba and Kajiyama's mechanical models of the human vocal cavity from transparent materials and showed that the models are extremely useful as educational tools. In Arai's models, two types of models were proposed: the cylinder-type model with the precise reproduction of Chiba and Kajiyama's original measurements (Fig. 1 (b)), and the plate-type model which is the step-wise approximation of the original measurements (Fig. 1 (a)). In both cases, a vowel-like sound is produced from the lip-end when a sound source is excited at the glottis end. An electrolarynx, which is itself an effective tool for education in speech science, is used as a sound source, because it produces a reasonably clear vowel sound through the models. As an alternative sound source, a whistle-type artificial larynx is also available.

Fig. 1: Mechanical models of the human vocal cavity; (a) the plate-type model of vowel /a/; (b) cylinder-type models (from left, /i/, /e/, /a/, /o/ and /u/); and (c) a model for nasalized vowel /a/.

Creating mechanical models of the human vocal cavity is not new. For example, from the literature we know that Kratzenstein (1782) and Von Kempelen (1791) made mechanical synthesizers back in 18th century (Gold and Morgan, 2000). After Chiba and Kajiyama published their book in 1941, many researchers designed models for their own research purposes. For example, Umeda and Teranishi (1966) created a mechanical model to investigate the relationship between vowel and voice qualities. Dang and Honda (1995), on the other hand, made a mechanical model to measure the effect of the pyriform fossa, side branches at the larynx.

Vocal tract models designed for education purposes can scarcely be found in the literature. Because we feel that mechanical models of the human vocal tract should be widely used for education, especially in the speech sciences, we have been developing educational tools since the early models designed by Arai (2001) (e.g., Arai et al., 2001; Usuki et al., 2001a; Yoshida et al., 2002, etc.).

2. The use of the models as educational tools

Textbooks and computer simulations are useful when acoustics is taught in a classroom environment. However, it is difficult to teach real-world physical constraints from books or digital simulations. For this reason, we believe physical models are essential to compliment the aforementioned tools.

We believe mechanical models are useful for educating students of various backgrounds and ages (Arai, 2002a; and Arai, 2002b). Physical models such as ours are especially suitable for non-technical students, because they are more intuitive. Also, we believe that education in acoustics is important not only for college-level students, but even high-school or potentially even elementary school students, for whom such hands-on models are even more important.

We have already used Arai's models (Arai, 2001) in the classroom and confirmed that they are powerful tools for education in acoustics and speech science. Because both types of models are transparent, they are both effective for making associations between the quality of a vowel and the location of constriction on the model. The cylinder-type model is particularly effective when we need to make a quick demonstration of vowel production because the model is 'sound-source-ready', that is, there is no set-up time. Source-filter theory is also easily taught with the cylinder-type model. By feeding several different sound sources into a model, we can teach that pitch is determined by the fundamental frequency of the sound source. At the same, students are able to see that the quality of a vowel is determined by the model itself and is not dependent on the sound source. Finally, we are able to show students that harmonic structure is independent from the resonances of the acoustic tube.

The plate type model has the advantages listed above, but also has some additional strengths over the cylinder type model. For example, although it requires more set-up time for lining up the plates, it is more appropriate for hands-on laboratory experiments because students can change the shape of the model arbitrarily. Perturbation theory in vowel production is also easily tested by using the plate-type model (Usuki et al., 2001b). By making a narrow constriction within a uniform tube, students can experience the resonance (formant) shift determined by the relationship between the locations of constriction and the nodes/antinodes of each vibration mode.

3. Advanced use of the mechanical models

We also developed an advanced model shown in Fig. 1 (c). This model simulates the nasalized vowel /a/ and is operated by attaching a side branch to the acoustic tube, simulating the nasal cavity (Saika et al., 2002). The dimension of the nasal cavity was based on Chen (1997). The velopharyngeal opening is adjustable with two screws. A resonator for a sinus is available, so that we can use the model either with or without the sinus.

Fig. 2 shows the effect of velopharyngeal coupling on the spectral envelope by this model. From this figure, the first formant is damped when the nasal cavity is coupled, and this tendency is even stronger when the sinus is attached. The produced sounds were perceived by listeners as nasalized vowels, and therefore, this model should be useful for teaching students about nasalization.

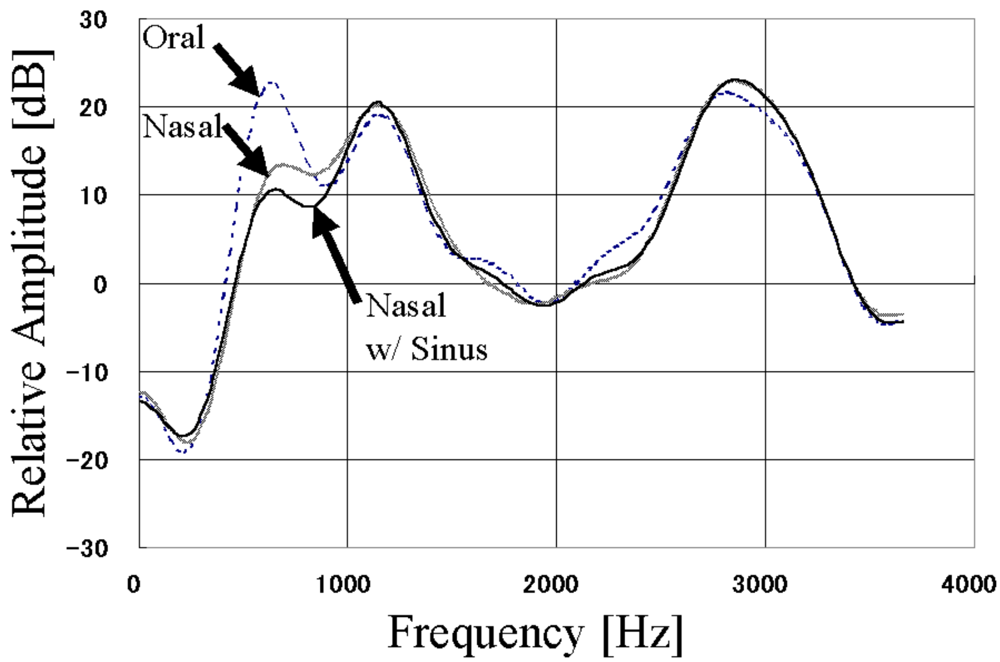

Fig. 2: Effect of the nasal cavity coupling on the spectral envelope (vowel /a/).

4. Summary

We discussed physical models of the human vocal tract as tools for education in acoustics and speech science. We confirmed that Arai's physical models are useful for educating students about vowel production. Beyond this, it might be worthwhile to develop an integration of the physical models with a computer simulation for more advanced education. These models as they exist now should also be used more widely, even in high school, middle school and elementary school. An early attempt has recently been launched (Maeda et al., 2002); further developments and efforts are needed.

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