NASALIZATION OF FRENCH VOWELS
Contribution of the nasopharyngeal tract and the sinuses

Gang FENG & Christian ABRY

Institut de Phonétique de Grenoble
Institut de la Communication Parlée
38031 Grenoble Cedex, FRANCE

ABSTRACT

In this paper, a complete simulation study on nasalization of 11 French vowels will be presented. All simulations, starting from different oral vowel configurations finally attain a nasality target : the nasopharyngeal tract. We will describe several rules for the pole-zero evolution structure. Afterwards, a study situating the "true" nasal vowels in the nasalized vowel frame will be presented. Finally the effects of sinuses on these simulations is discussed.

INTRODUCTION

The conception of a nasality target has been proposed in a preceding study [1,2]. This target, articulatorily represented by the nasopharyngeal tract, can be characterized by its first two spectral peaks : 300 and 1000 Hz. In order to simulate more realistically these acoustic characteristics, we suggested using a small acoustic equivalent nostril for the nasal tract. It has been shown that this approach can provide a better match for the first spectral peaks by comparing it with the nasal tract (alone) and nasopharyngeal tract sweep-tone measurements.

Since we proposed that all nasal vowels should be considered as dynamic trends towards the nasality target, a complete simulation of transfer functions from oral vowels to their corresponding nasopharyngeal configurations seems necessary : i.e. we should examine dynamically all of the coupling degrees.

In this paper, we will present the simulation results for the nasalization of 11 French vowels. For each vowel, we start from the oral configuration, which corresponds to the highest velum position. Then we change progressively the velum position, representing different coupling degrees. Finally the nasopharyngeal configuration with the velum lowered to the tongue is attained.

Such simulations give us a continuous transfer function evolution for all the French vowels. We tried to show several rules from these simulations that should be useful for analysis and synthesis of nasal vowels.

On the other hand, we tried to situate the "true" nasal vowels in this nasalized vowel frame, especially the nasal vowel [ɑ̃], which is often considered as the most difficult to synthesize.

After examining the simulation results that establish the basic pole-zero evolutions, we shall consider the sinus in these simulations. It will be shown that the main effect of the sinus is to make the spectrum more complex.

1. THE SIMULATION MODEL AND AREA FUNCTIONS

We adopted the classical electrical-line vocal-tract model in our simulations to calculate transfer functions in the frequency domain [3]. The area functions used for the 11 French vowels were taken from BOE [4] and MRAYATI [5], slightly modified by FENG [6].

In our simulations, one crucial problem was to determine the area function in the velum region for different coupling degrees. Without sufficient physiological data, we were obliged to make an approximation, which appeared reasonable. We simply divided the area at the coupling point (i.e. around the extremity of the velum-uvula) into two parts : one corresponding to the input of the nasal tract and the other to the input of the oral tract. For the different velum positions, we chose a series of area-ratio (partial area / total area) as follows : 0.0, 0.025, 0.05, 0.1, 0.3, 0.7, 0.9, 0.95, 0.975, 1.0. The two sections (section length : 1cm) just after the coupling point in both the nasal and oral tracts are then determined by a linear interpolation.

2. THE POLE-ZERO EVOLUTION STRUCTURE

Before discussing real vowel simulations, it should be useful to show here a simplified simulation that will provide a pole-zero evolution structure.

In this simulation, a parallel L-C(-R) circuit is used to study the coupling problem. In the system, each of the branches is composed of a 2-order L-C(-R) circuit, having two resonance frequencies and a zero-impedance frequency. One can adjust the access-coefficient of each branch by modifying its impedance, thus changing the coupling degree of the system. The transfer function of this system is defined by the ratio : the sum of the two output currents / input current.

When the access-coefficients of the two branches are changed continuously, one obtains an evolution of the system transfer functions. Figure 1 is a typical example. The highest and the lowest transfer functions of this evolution correspond to the two extreme situations in which one of the two branches is totally connected and the other cut off. So the system transfer function corresponds to only one of the two branches, having two poles and no zero. Between these two extremities, the transfer functions present three poles and one zero, due to coupling. The middle of the evolution shows maximal coupling since the two branches possess the same access-coefficients.

One can obtain different evolutive images when the parameters of the two branches are changed. It is not difficult to prove that, for this system, all evolutions can be classified in several structures, shown in Figure 2. Here F11, F12 and Z1 denote respectively the two resonance frequencies and the zero-impedance frequency for one branch, and F21, F22, Z2 for the other branch.

Naturally, the real coupled vocal tract model is more complex than this system. However, it has been found that impedance variations of the nasal tract and the oral tract, during different coupling degrees, are similar to the above system. Moreover, we are mainly interested in the first two formant region. So the above pole-zero evolutive structure remains instructive for the study of real simulations.

3. NASALIZATION OF THE 11 FRENCH VOWELS.

We will now examine the simulation results for nasalization of the 11 French vowels. We will begin with the extreme cardinal vowels [i], [u] and [ɑ], since they determine the limits of the vocalic space.

For each vowel, 10 transfer functions have been calculated and presented, corresponding to the series of area-ratios described above (Fig. 3). The lowest one represents the transfer function for the oral vowel and the highest that for the corresponding nasopharyngeal tract. Between these two extremes, figure transfer functions for the nasalized vowels with different coupling degrees.

For [i], starting from the first two formants 240 - 2270 Hz, we attain the nasopharyngeal structure with 240 - 1090 Hz. The evolution firstly shows the appearance of a "shoulder" to F1 for [i], and then this peak finally forms the second pole of the nasopharyngeal tract (the second typical pole). As for F2 for [i], it ends by joining the zero and then disappears. This evolution is very similar to the structure presented in Figure 2-h.

In such a transition, analysis and perceptual knowledge provide for us a domain in where the vowel can be validated as nasal [7].

Concerning the production for [u], the evolution towards the nasopharyngeal tract is carried out like a slight elevation of the second pole, the first one remaining - as is the case for [i] - relatively stable. Between these two poles evolves the first pole-zero pair : this corresponds to the usual structure (e) of Fig. 2.

We can obtain, here also, a rather large domain of validation for nasality [7].

The transition for vowel [ɑ] is in the same category as for vowel [i] (but corresponding to the structure in Fig. 2-d) :

- an addition of a peak, as is the case for [i], but here it concerns a low nasopharyngeal peak ;
- a disappearance of a formant, like for [i], but it concerns the first formant here.

The second formant shifts downwards and becomes the high nasopharyngeal peak.

Sweep-tone measurement data [8] confirms here that the typical vocalic domain for [ɑ̃] (for perception, cf. [9]) is rather close to a configuration presenting a maximum velopharyngeal opening - contrary to [i] and [u] that offer a wider validation domain. These simulation results thus correspond to the fact that the low vowels demand a greater velopharyngeal opening in order to be categorized as nasal vowels (reviewed in [10]).

Disparity of nasal correlates for these three types of extreme vowels - already cited in the literature - may seem rebelious to any attempt in simplifying the articulatori-acoustic correspondence.

Addition of poles (so-called "nasal poles"), a high one for [i], a low one for [ɑ] ; evolution of the second pole, lowering of "F2" for [ɑ], elevation of "F2" for [u]..., all of these effects are coherent only when considered as one tendency towards a single objective : acquisition of two essential nasopharyngeal tract characteristics or of one only if the vowel already possesses the other.

The remaining vowels would be situated between these three extremes, with the following major modifications :

- acquisition of a high pole and disappearance of F2 for [i], [y], [e], [ø], [ɛ], and [œ] ;
- lowering of F1 and/or elevation of F2 for [u] and [o] ;
- acquisition of a low pole, disappearance of F1 and lowering of F2 for [a],

[ɑ] and [ɔ].

To summarize further we notice that we are confronted with two topological criteria : - F1 becomes a low pole, the case in [i,...,œ] and [u,o], or disapppears [a, ɑ,ɔ] ; - F2 becomes a high pole, the case in [a, ɑ, ɔ] and also [u,o], or disappears [i,...,æ].

Consequently, when F1 disappears the vowel acquires a low pole [a,ɑ,ɔ] ; if such is the case for F2, the vowel acquires a high pole [i,...,æ]. These acquisitions are, in the final analysis, the most crucial properties. The topology of these acquired poles thus remains the most useful in categorizing our vowels.

It is certain that a continuous passage from one of these categories to the other is possible : or a discontinuous one if emphasis is made on topological "catastrophies", namely the appearance of a pole on the right or left of a formant (the case of [ɛ] vs. [a], etc.).

4. THE NASAL VOWEL [ɑ̃] IN THE NASALIZED VOWEL FRAME

We shall now examine how the true French nasal vowels are inserted in the nasalized vowel frame. The vowel [ɑ̃] will be taken as an example since it is related to : - the realizations of [ɛ̃], or rather the nasalization of [ə] or [ä̃] [11,12] ; - the realizations of [ɔ̃] : more open than [o] (at times even more than [ɔ]) concerning the tongue but very close to the latter with regards to the lips [13,14].

In its oral part, the area function of [ɑ̃] (according to [14]), is close to [ɔ] as to vocal tract length (protrusion-closion of the lips, lowering of the larynx), but different when it comes to pharyngeal constriction size. [ɑ̃] seems to be different from [ɑ], both for vocal tract length ([ɑ] is less protruded for the two speakers in [14]) and for pharyngeal constriction (the same speakers have a tendency to narrow this part of the vocal tract).

These available radiographic data [14] were converted to area functions for their oral part (using coefficients from [15]). The corresponding transfer functions were then calculated. We present here one transfer function for [ɑ̃] to compare with two oral vowels [ɑ] and [ɔ] (Fig. 4).

The oral configuration of [ɑ̃] presents the smallest distance between the two first poles. The [ɔ] formants are lower than those for [ɑ] due to a different lip opening.

[ɑ] compared with [ɔ] shows a decrease of the constriction area in the pharynx. This explains - the second formant having a great sensitivity in this zone (cf. FANT's nomograms [16]) - the relative lowering of F2. The elevation of F1 seems to be a result of a slight continuous retreating of the constriction (ibid.).

A transition from the oral configuration of [ɑ̃] to its nasopharyngeal one is then simulated with the same procedure as presented in section 3.

Figure 5 shows a similar evolutive structure as those of the nasalized vowels [a,ɑ,ɔ]. A lower pole appears below the first formant, then tends towards the first nasopharyngeal peak. Only the evolution of the zero presents a little difference, having a (g)-type structure in Figure 2. However, the acquisition of a low pole on the left of F1 puts this vowel in the phonetic category where [a,ɑ,ɔ] are already situated.

5. THE EFFECTS OF SINUSES

The preceding similations without sinuses provide a clear image of pole-zero evolutions for the nasalized vowels. But knowing the complexity of the nasal tract labyrinth, it seems unrealistic to neglect the sinus cavities (mainly the maxillaries). Here, we will present a simulation result (Fig. 6) in which the maxillaries sinuses were simulated by a Helmholtz resonance [17,18]. Due to the large variability of sinus sizes, and consequently of their acoustic properties [19], we took just as an example a sinus having a volume of 18cm3 and a resonance frequency of about 650 Hz.

Comparing these results with Figure 3, we can see that the main characteristics of the pole evolution structures are preserved in the simulations with a sinus. But a pole-zero pair, resulting from the presence of the sinus, is added to transfer functions, thus changing slightly their structures. So the main effect of this sinus seems only to add more complexity to the nasal spectrum.

CONLUSION

We have tried to establish a complete pole-zero evolution structure for the nasalization of the 11 French vowels. All evolutions, starting from different vowels finally attain a nasality target : the nasopharyngeal tract. This trend versus the complexe pole-zero evolutive structures allows us to propose a common strategy for the nasalization of all vowels. We can place the "true" nasal vowels for French in this frame. To make the simulations more realistic we took into account the complex effects introduced by the sinuses. But the complexity of the real nasal vowel spectrum seems to demand more elaborate simulations, in which the nasal tract would be better modeled, and the effect of the source (the glottal formant) be taken into account [20].

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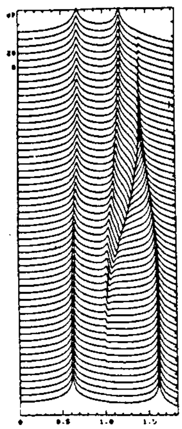


Fig 1

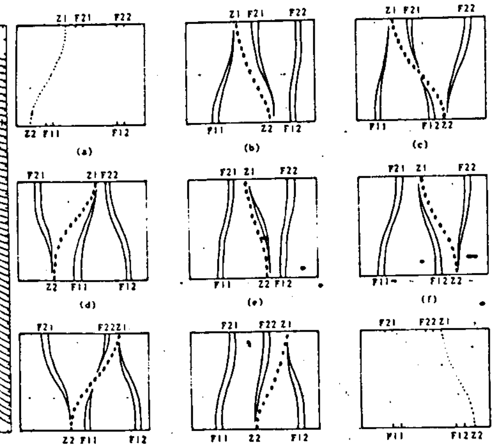


Fig.2

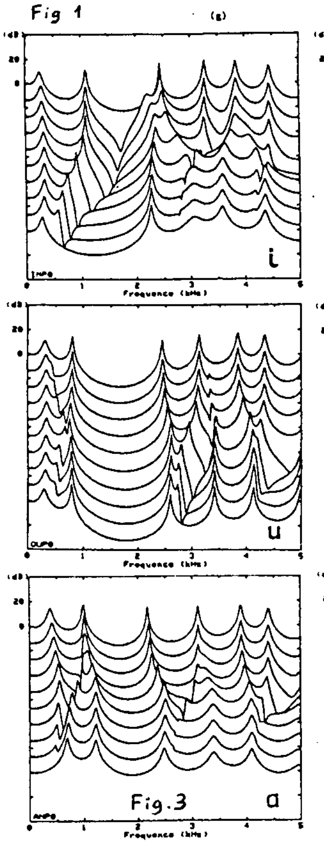


Fig.3

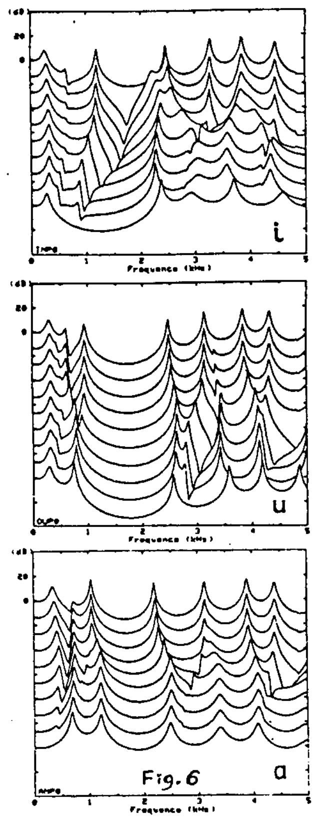
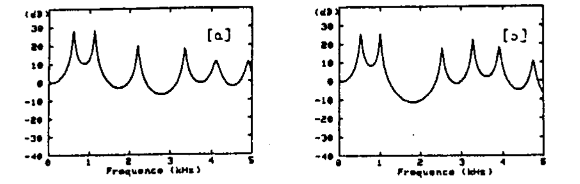


Fig.6



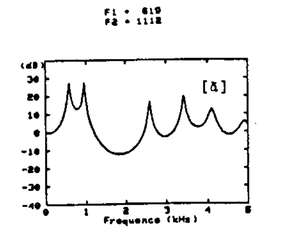


Fig.4

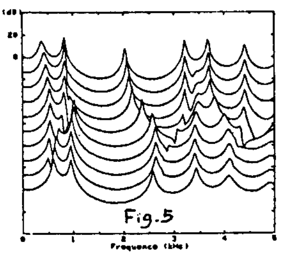


Fig.5