Resonance measurements in the case of tenor voice

Nathalie Henrich[1], Joe Wolfe[2] and John Smith[2]

(1) Laboratoire d'Acoustique Musicale (CNRS, UPMC, Ministère de la Culture), Paris, France
(2) School of Physics, University of New South Wales, Sydney, Australia
henrich@lam.jussieu.fr, j.wolfe@unsw.edu.au, john.smith@unsw.edu.au

Abstract

A method of real-time non-invasive acoustic impedance spectrometry is applied to explore the resonance strategies of eight tenors in modal register (laryngeal mechanism 1). Four vowels ([ɑ],[ɜ],[ɔ],[ʉ]) are studied over the whole frequency range of each singer. The results show that the tenors tend to maintain their first two resonances R1 and R2 at frequencies that depend at most very weakly on pitch, except for the vowel 'oo' ([ʉ]) for which a tuning of the first resonance with the first harmonic (fundamental frequency) can sometimes be observed at high pitch. The higher resonances R3 and R4, which are located in the singers' formant region, do not merge, and they also vary little with pitch. Over the whole tessitura, the frequency separation between R3 and R4 varies little with pitch and is rather less than that between R2 and R3.

1. Introduction

The source-filter theory developed by Fant in 1960 is a first order model of voice production. The acoustic source is generated by the periodic vibrations of the vocal folds. It is then filtered by the vocal tract, which acts as a variable impedance matcher between the vocal folds and the external radiation field. The impedance matching is most efficient, and so produces enhanced vocal power, around the resonances of the vocal tract. These resonances produce local maxima in the power spectrum, which are commonly called formants. The first two formants are known to be important in vowel identification, and the next few ones are of importance for voice quality and speaker identification.

A common approximation in the source-filter theory is the independence of source and filter. This approximation may be inappropriate in the case of singing, as one major facet of singing technique consists of working on the coupling between the sub-glottal (breathing system and vocal folds) and the supra-glottal cavities, in order to enhance vocal efficiency. This point underlines one limitation for the use of formant detection algorithms based on the source-filter theory (linear prediction, discrete all-pole modeling, cepstral analysis, …) to investigate the acoustics of the vocal tract in the case of singing. A further problem in using the voice itself to deduce properties of the tract arises in the case of high pitch sounds, for which the harmonics are too widely spaced.

The method developed by Epps, Smith and Wolfe (Epps *et al.*, 1997) to measure the acoustic resonances of the vocal tract during speech seems a promising tool, as it gives information about the acoustic resonances directly, for sustained vowels spoken or sung at any pitch. The vocal tract response is studied by injecting a carefully synthesised, broad band acoustic current at the mouth, while the subject is phonating. This method has already proved useful in the study of resonance strategies used by soprano singers, who tend to tune the lowest resonance (R1) of the vocal tract close to that of the pitch frequency when singing isolated notes from an ascending scale (Joliveau *et al.*, 2003).

In the present study, we aimed to apply this measurement technique for exploring the resonance strategies in the case of tenor voice.

2. Material and Methods

2.1. Singing database

Eight trained tenors were recorded: 5 of them are professional singers (T1, T2, T3, T5, T6), 1 is a semiprofessional (T8) and 2 are amateur singers (T4 and T7). Their age ranged from 20 to 49 years. They were asked to sing four vowels, indicated by the investigators:
- ɑ as in the English word 'hard'
- ɜ as in the English word 'heard'
- ɔ as in the English word 'hoard'
- ʉ as in the English word 'who'd'

They were asked to sing these vowels on several notes, which were chosen by the investigators with regard to their tessitura, and their comfortable lowest and highest notes. The pitches were indicated to the singer with a glockenspiel. They were asked to sing at a comfortable level in their trained singing style, preferably piano to mezzo-forte, and if possible with a reduced amount of vibrato. Each sung note was sustained for about 4 seconds, and it was not repeated. At the end of a recording session, selected notes were repeated a few times for the purpose of statistical analysis.

2.2. Real-time impedance measurement: principle of the method

The method developed by Epps, Smith and Wolfe (1997) allows the direct measurement of the acoustic resonances of the vocal tract for sustained vowels spoken or sung at any pitch. The vocal tract response is studied by injecting a carefully synthesised, broad band acoustic current at the mouth, while the subject is phonating. This current source, with very high output impedance, drives the impedance $Z_{//}$, which is the parallel combination of the acoustic impedance of the vocal tract Z_{vt} and the radiation impedance at the lips Z_r:

$$Z_{//} = \frac{1}{\frac{1}{Z_{vt}} + \frac{1}{Z_r}} = Z_{vt} * Z_r / (Z_{vt} + Z_r)$$

At the frequencies of interest (0.1-4 kHz) and close to the lips, Z_r is inertive and it is approximately linearly dependent on the frequency:

$$Z_r \approx jkr\alpha Z_0$$

with $j = \sqrt{-1}$, $k = 2\pi f / c$ the wave number with frequency f and speed of sound c, r the radial distance to the lips, α a geometrical factor determined by the solid angle available for radiation and Z_0 the specific acoustic impedance.

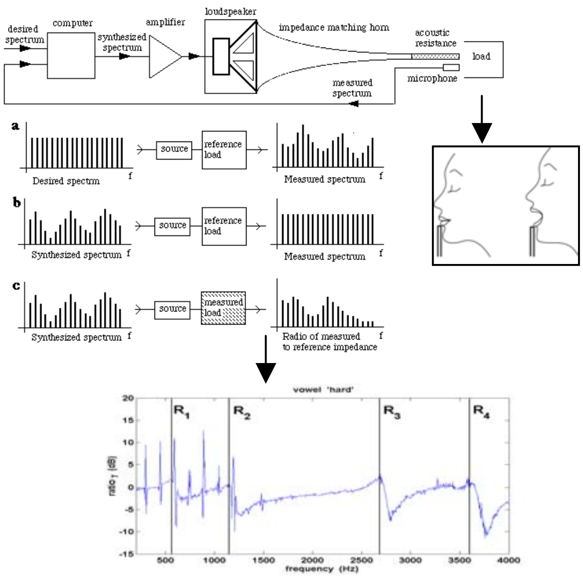

Figure 1: *principle of the method for real-time impedance measurement*

Prior to the measurements, Z_r is determined by a calibration measurement made with the singer's mouth closed.
The ratio $\gamma = Z_{//}/Z_r$ is plotted.

$$\gamma = Z_{vt} / (Z_{vt} + Z_r).$$

Making the assumption that the frequency variation of $\boldsymbol{Z_r}$ is much less than that of $\boldsymbol{Z_{vt}}$, γ has maxima when $\boldsymbol{Z_{vt}}$ has maxima.

3. Results

The results show that the tenors tend to maintain their first two resonances R1 and R2 at frequencies that are at most weakly dependent upon the pitch (see Figure 3). At high frequency, a tuning of the first resonance to coincide approximately with the first harmonic (fundamental frequency) can sometimes be observed for the vowel [ʊ] (as in "who'd") (see Figure 3, tenor 6 and Figure 4, tenor 4). These results are in agreement with previous results found by Titze *et al.* (1994) in the case of six tenors using an analysis-by-synthesis method.

In individual cases, a correlation can sometimes be observed between the first two resonances and the fundamental frequency, as illustrated Figure 3 (tenor T2) and Figure 4 (tenor T4).

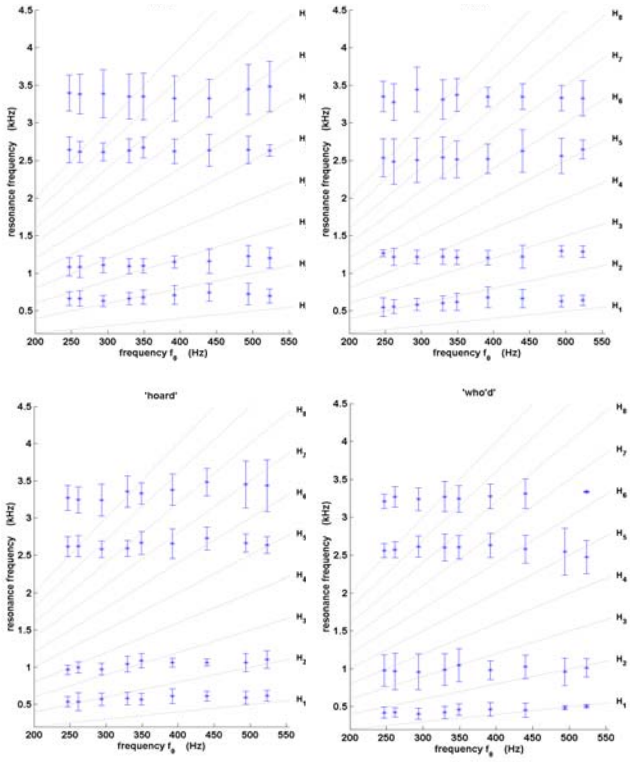

Figure 2 : *average vocal tract resonances as a function of fundamental frequency, for each of the four studied vowels.*

The higher resonances R3 and R4, which are located in the singers' formant region (Sunberg, 1987), do not merge. As illustrated in Figure 3, Figure 3 and Figure 4, they remain in a precise frequency region. Over the whole tessitura, the frequency separation between both resonances depends at most weakly upon the pitch.

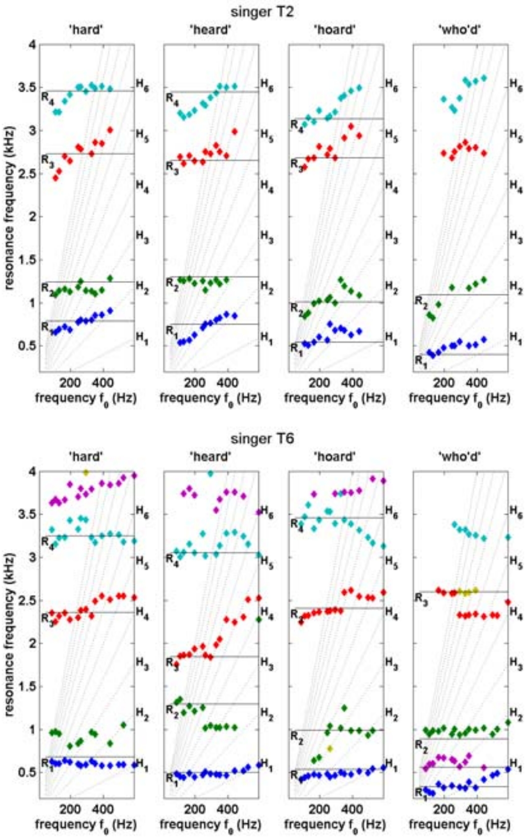

Figure 3: *Results for professional tenors T2 and T6. The horizontal plain lines correspond to the resonances measured during speech. The fine lines are $H_n = nf0$, where n is an integer. Formant tuning, as practised by sopranos, occurs when the data follow such lines.*

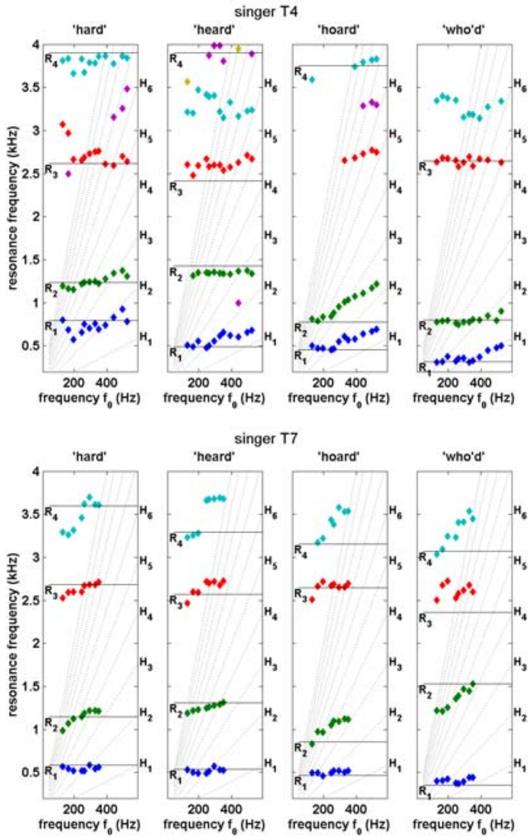

Figure 4: *Results for amateur tenors T4 and T7. The horizontal plain lines correspond to the resonances measured during speech. The fine lines are $H_n = nf0$, where n is an integer.*

4. Discussion

In the tenors studied here, there was relatively little tuning of resonances to match harmonics of the voice. That which was observed occurred at high pitch for the vowel u. This is the only vowel studied here for which f_0 and R1 overlap in range. None of the singers studied here showed a fusion of R3 and R4. The spacing between R3 and R4 was, however, substantially less than that between R2 and R3.

5. References

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