Buenos Aires – 5 to 9 September, 2016
Acoustics for the 21st Century…

PROCEEDINGS of the 22nd International Congress on Acoustics

General Musical Acoustics: Paper ICA2016-207

Soprano singing, with and without resonances

Laura Wade[a], Noel Hanna[b], John Smith[c], and Joe Wolfe[d]

[a] School of Physics, University of New South Wales, Australia, laura.c.wade@gmail.com
[b] School of Physics, University of New South Wales, Australia, n.hanna@unswalumni.com
[c] School of Physics, University of New South Wales, Australia, john.smith@unsw.edu.au
[d] School of Physics, University of New South Wales, Australia, j.wolfe@unsw.edu.au

Abstract

Oscillating vocal folds are acoustically loaded by resonant acoustic ducts upstream (trachea) and downstream (vocal tract). Further, the frequency range of sopranos means that they must deal with the first resonance in each duct; indeed, they often tune the vocal tract resonance near the oscillation frequency. So, what happens when the resonances of the vocal tract (and the large impedances they produce) are removed? In this study, sopranos sang with their lips sealed around an acoustically infinite pipe, which reduces the impedance of the first tract resonance (R1) to a small, resistive load. The singers performed pitch glides over the frequency range F3-C6 (nominally 175-1049 Hz), which covers their subglottal resonance and also the range where R1 would lie in normal singing. In general, no instabilities were produced. This ability to sing into a non-resonant downstream acoustic load, and on either side of the upstream resonant load, demonstrates that a particular phase of load (inertive or compliant) is not essential for stable vocal fold oscillation. What happens when the acoustic load suddenly changes? Later, the same singers were asked to sing a fixed pitch into the same non-resonant load while keeping their eyes closed. A plug was rapidly removed outside the lips, which introduced an acoustic reflection similar to an open mouth at the interface with the outside air, and therefore a resonant load. This abrupt change to the acoustic load on the vocal folds triggered brief instabilities in vocal fold oscillation. A return to steady oscillation after the change was possible regardless of the sign of the acoustic loading (inertive or compliant), which together with the experiment described above, suggests that stable vocal fold oscillation is possible into a wide range of acoustic loads.

Keywords: soprano, vocal tract, resonance, singing, non-resonant ducts, acoustic loads

Soprano singing, with and without resonances

1 Introduction

Sopranos are typically asked to sing over a frequency range from C4 - C6 (nominally 261-1046 Hz). This range overlaps with the range of the first acoustic resonance of the vocal tract f_{R1}[1] and includes the frequency of the first resonance of the subglottal tract f_{Sg1}. These resonant ducts provide respectively the downstream and upstream acoustic loads on the glottal source. The acoustic impedances of the ducts are in general reactive: each impedance can be inertive (mass-like) or compliant (spring-like) depending on whether the frequency of vocal fold oscillation f_o lies below or above the frequency of the impedance peak, respectively. Models of vocal fold oscillation, (*e.g* [2]) suggest that the reactance of the load on the vocal folds may affect their oscillation either beneficially or detrimentally. This is one possible explanation for the observation that sopranos often tune f_{R1} to be near f_o e.g. [3] and [4]. Another possible explanation for this tuning is that singers use such tuning to maximise radiated power output (sound level) for a given power input.

2 Materials and methods

2.1 *Singers*

The study described here is part of a larger study of eight volunteer female singers whose formal vocal training and experience is summarised in Table 1. All were speakers of Australian English. The experimental protocol was approved by the university's Human Ethics Committee.

Table 1: Details of the experimental subjects.

Subjects	Age	Singing Experience
S1	23	2 years formal training, 6 years choral singing
S2	22	16 years formal training, formal teaching qualifications
S3	22	4 years choral experience
S4	23	6 years formal training, choral and opera experience
S5	19	6 years formal training, choral experience
S6	23	2 years of formal training, 6 years choral experience
S7	25	8 years formal training, 19 years choral experience
S8	20	2 years formal training, 6 years choral experience

[1] Where f_{R1} denotes the frequency of the first acoustic resonance R1 of the supraglottal vocal tract in the nomenclature recommended by Titze *et al.* [1].

2.2 *Resistive load*

The singers were asked to sing with their lips sealed around an acoustically infinite pipe, with internal diameter 26.2 mm, external diameter 32 mm and length 197 m; see Figure 1. The characteristic impedance of this pipe approximates that of the vocal tract itself. Resonances are produced in ducts when reflection coefficients approach unity. Since the acoustic reflection coefficient at the lips is well below unity, the pipe reduces the magnitude of the impedance of the first acoustic tract resonance (R1), as seen by the vocal folds, to a small, resistive load, *i.e.* effectively removing R1.

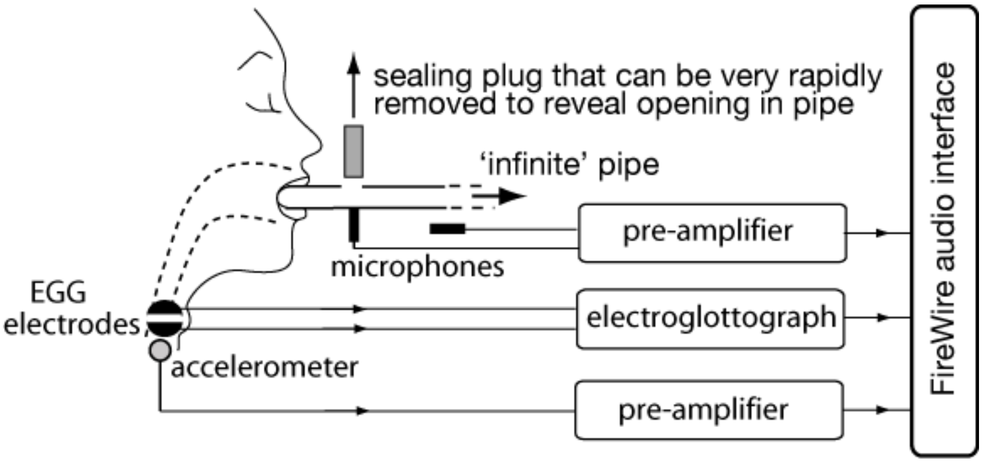

Figure 1: Schematic diagram (not to scale) showing the configuration used for the experiments.

2.3 *Pitch glides without resonances*

The singers performed ascending and descending pitch glides over the frequency ranges C5 to F3 (523 to 175 Hz), and C6 to F4 (1047 to 349 Hz), which covers the range of f_{R1} in normal speech (~300 Hz ≤ f_{R1} ≤ ~800 Hz) and the frequency of the first subglottal resonance f_{sg1} (560 ≤ f_{sg1} ≤ 700 [5, 6, 7]). It is worth noting that 175 Hz is below the standard soprano range, so most singers started in their modal (chest or M1) voice and changed to their head (M2) voice, while increasing f_o.

2.4 *Sudden reintroduction of vocal tract resonances*

Later, the same singers were asked to sing a series of sustained notes of fixed pitch (an ascending chromatic scale from C3-C6) into the same non-resonant load while keeping their eyes closed. During each sustained note, a plug (see Figure 2) located 30 mm from the lips was very rapidly pulled out by the experimenter at an unexpected time using a cord and pulley arrangement. Pulling the plug opens the duct to the air outside and so suddenly introduces an acoustic reflection similar to that of an open mouth. This changes the downstream acoustic load experienced by the vocal folds from resistive to reactive.

Since the plug was 30 mm from the lips and has an end effect similar to that of the mouth, it extends the length of the vocal tract length by approximately 30 mm. To estimate the effective f_{R1} produced by this opening outside the lips, the subjects' vocal tract lengths were first estimated by measuring f_{R1} and f_{R2} through the lips by impedance spectrometry as described elsewhere [8, 9]. This provides estimates of the length $l = c/4f_{R1}$, $3c/4f_{R2}$, where c = 354 m·s^{-1} in saturated air at 37°C. An additional 40 mm (including end effect) was added to account for the position and end effect of the plug. This resulted in f_{R1} values, as seen by the vocal folds, of 380-510 Hz, values that would be produced in women's speech with small lip opening. The sign of the reactive load (inertive or compliant) depends on the relationship of the sung note f_0 to f_{R1}. The chromatic scale used therefore included notes with $f_0 < f_{R1}$, $f_0 \sim f_{R1}$ and $f_0 > f_{R1}$.

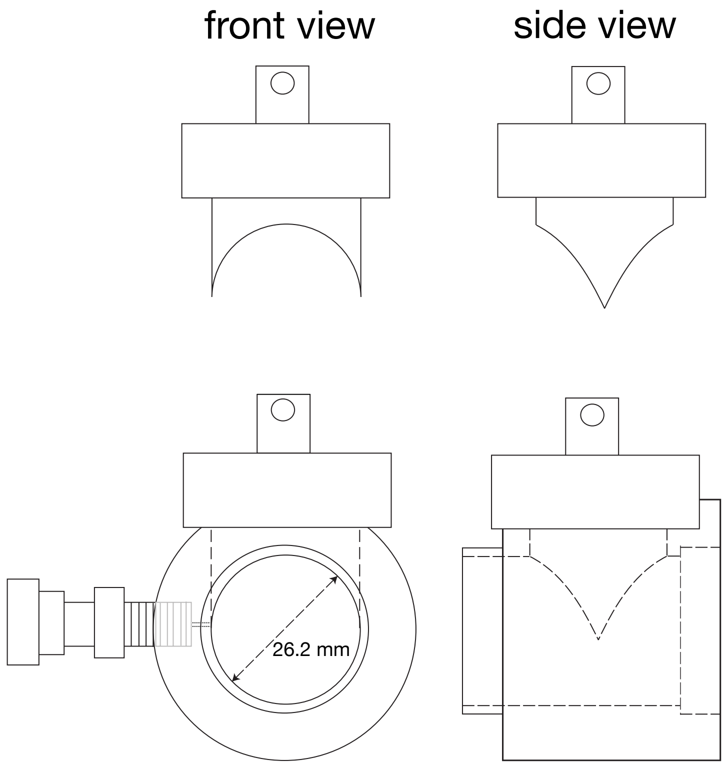

Figure 2: Schematic showing the plug and how it fits into the infinite pipe to ensure the cylindrical geometry of the infinite pipe is maintained. Note that the additional port in the bottom left is for a microphone with a 1 mm diameter hole. A microphone was present but its signal was not analysed in the current study.

2.5 *Measurements of acceleration and sound*

Throughout the experiments, vocal fold oscillation was monitored with a dual channel electroglottograph (EG-2, Glottal Enterprises, Syracuse, NY). A small accelerometer (Hot Spot, K&K Sound Systems, Coos Bay, Oregon) was used to determine the frequencies of the subglottal resonances following the method of Lulich *et al.* [7]. Sound was recorded inside the infinite pipe with a 1/4" pressure-field microphone (4944A, Brüel & Kjær, Denmark) and outside the pipe (approximately 10 cm away from the lips), with a condenser microphone (RODE NT3, Sydney, Australia). All signals were sampled at 44.1 kHz with 16-bit resolution using a FireWire audio interface (MOTU 828, Cambridge, MA) and subsequently analysed using PRAAT 5.3.75

(Boersma and Weenink, 2015). A schematic of the experimental apparatus is shown in Figure 1.

3 Results and discussion

3.1 *Can singers sing into a resistive (non-reactive) downstream load? Do they experience instabilities when crossing their subglottal resonance?*

The frequency of the first subglottal resonance f_{Sg1} was 630±50 Hz for all singers, which is consistent with previously reported values for women (e.g. [5, 6, 7]). For the experiments in which the subjects sang pitch glides into the infinite pipe. This resonance was the only one present when subjects sang pitch glides into the infinite pipe.

In general, few instabilities were produced when subjects sang pitch glides into the infinite pipe. A typical EGG spectrogram is shown in Figure 3. One subject consistently showed a discontinuous pitch jump at the top of her range, around 800-1050 Hz. Three subjects experienced an unsteady pitch in the range 200-300 Hz in half of their glides. Since this frequency range is well below f_{R1}, and at the low end of the soprano range, it is likely that this instability is due to a change in their mechanism of vocal fold oscillation from chest to head (M1-M2), although in these cases an abrupt change in the form of the EGG signal was not observed.

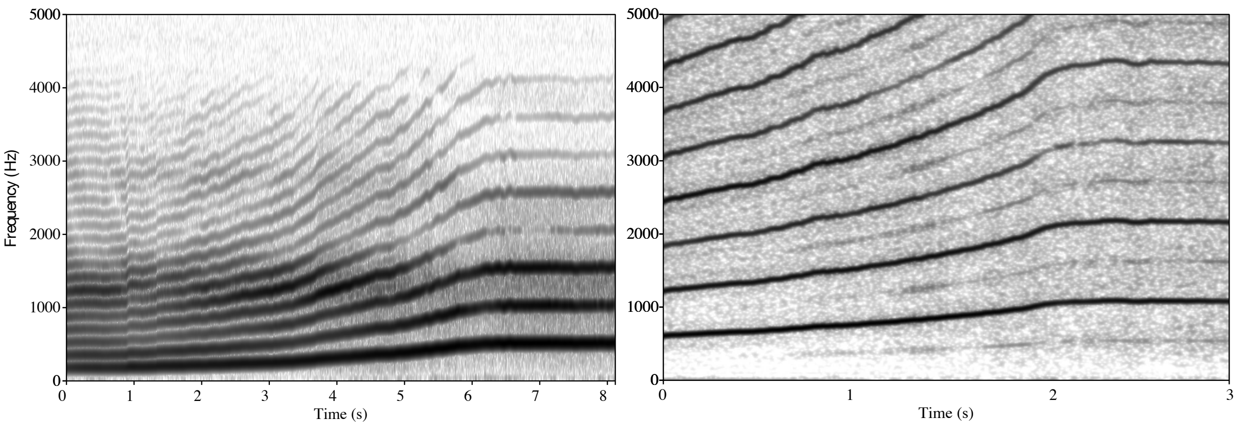

Figure 3: Example EGG spectrograms showing sections of a low (F3 –C5, 175 to 523 Hz) and high (F4 to C6, 349 to 1047 Hz) pitch glide into the infinite pipe with no large instabilities.

This ability to sing into a resistive, i.e. non-resonant, downstream acoustic load, and at frequencies above and below the frequency of the impedance peak of the upstream subglottal duct, demonstrates that a particular phase of reactive load (inertive or compliant) is not essential for stable vocal fold oscillation.

3.2 *What happens when a downstream resonance is abruptly reintroduced?*

When the sung notes were interrupted by the plug being pulled (abruptly changing the downstream load) several effects were observed. These are described and illustrated in Figure 4.

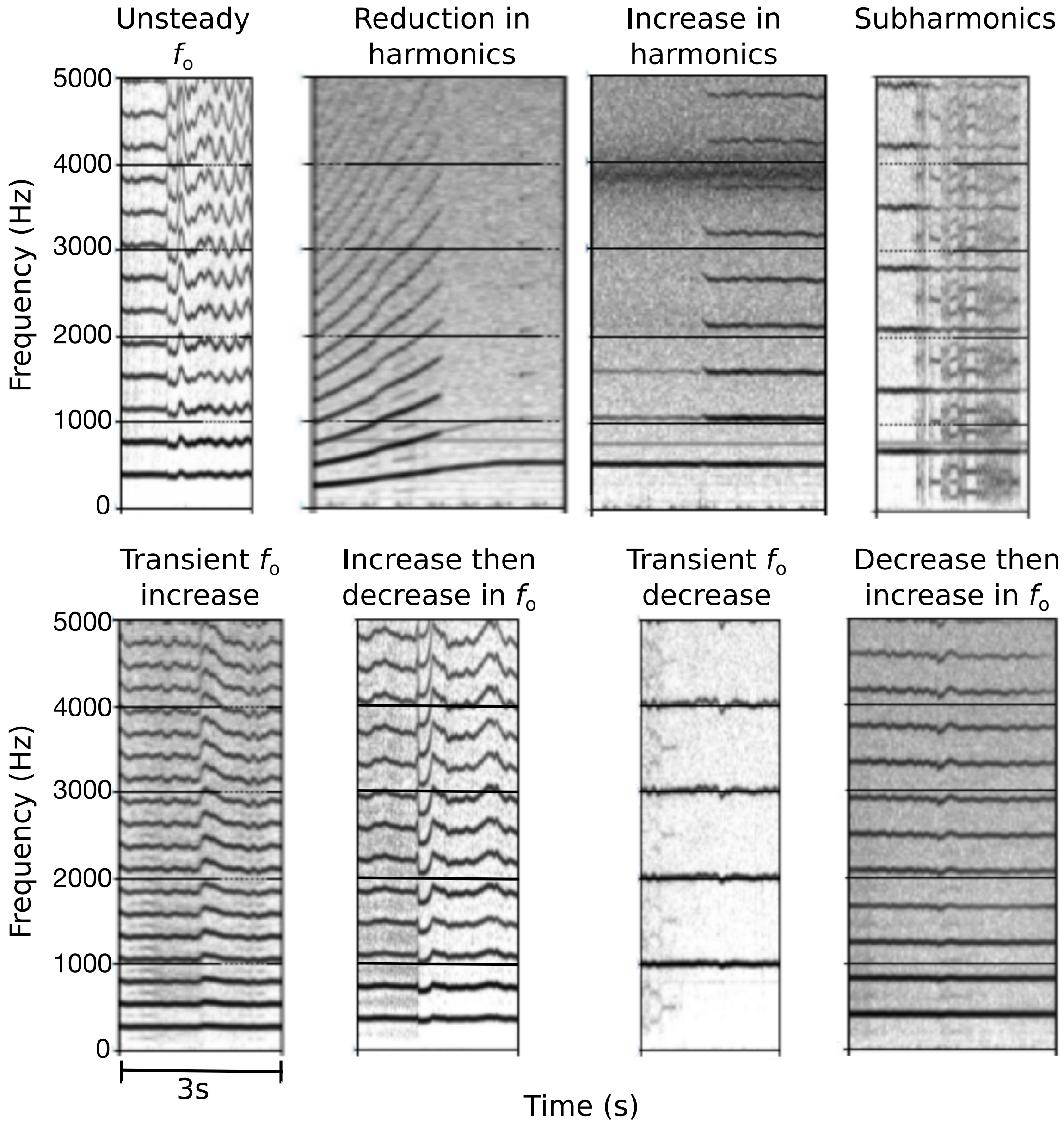

Figure 4: Spectrograms showing the eight different effects identified following sudden reintroduction of vocal tract resonances.

Although eight different types of instability were identified, most were observed infrequently. Only the transient increase in f_o was observed more than 50% of the time for particular notes. The fraction of cases exhibiting the transient upwards pitch shift is shown for each sung note as a function of f_o in Figure 5.

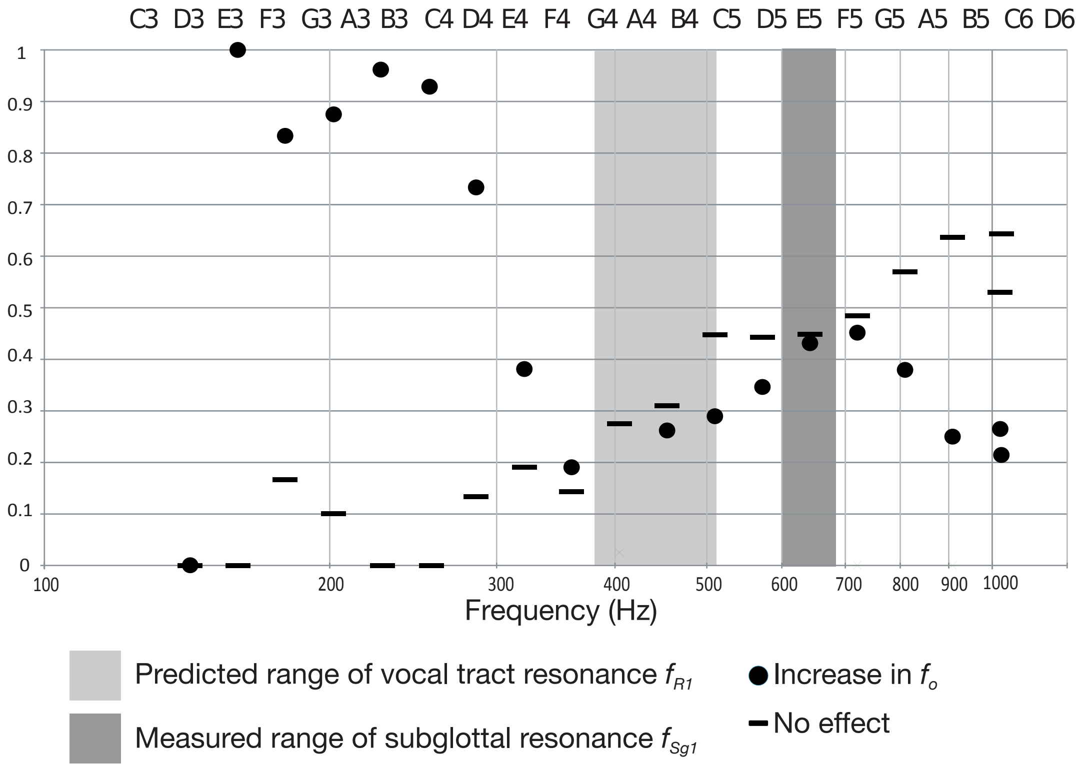

Figure 5: The fraction of examples showing a transient pitch increase (or no effect) during the pitch glides, plotted as a function of pitch (top axis) and frequency (bottom axis). Singing frequencies are grouped to the nearest minor 3rd.

In Figure 5, consider first the cases when the load changed from resistive to inertive, i.e. $f_o < f_{R1}$: these are the examples to the left of the left hand shaded region. In the majority of these cases, the load change produced a sudden pitch increase followed by a return to steady oscillation. When the downstream load changed from resistive to compliant $f_o > f_{R1}$ – the region immediately to the right of the left hand shaded region pitch increases occurred in only about 30% of cases.

Consider now the case of the plug being pulled during a steady note with $f_o > f_{Sg1}$. Figure 5 shows that suddenly introducing a strongly compliant subglottal impedance has no effect in more than half of the cases. Again, crossing the subglottal resonance ($f_o \sim f_{sg}$) has no marked effect on the response of the subjects to the plug pull.

It should be noted that pulling the plug in this experiment is also expected to produce a slight increase in the mean transglottal pressure, because of the finite pressure excess in the mouth required to move the air through the external duct. Increasing the subglottal pressure suddenly (e.g. by pushing a subject in the chest, without warning [10]) is reported to increase f_o. So the changes noted here might be due to that effect rather than to the sudden introduction of the inertive or compliant load.

4 Conclusions

The results of this study suggest that sopranos are capable of singing without instabilities into a variety of upstream and downstream loads (inertive, compliant and resistive), provided that the loads do not vary quickly. They do not require a reactive (inertive or compliant) acoustic load downstream (vocal tract resonance) or upstream (sub-glottal resonance) to produce stable vocal fold oscillation. However, abrupt changes to the downstream load do provoke transient pitch changes, particularly when the load changes from resistive to inertive.

Acknowledgments

We thank our volunteer subjects and the Australian Research Council. NH was awarded an ICA-ASA Young Scientist Conference Attendance Grant to present this paper at ICA.

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