Measuring vocal-tract impedance at the lips: model, hypotheses and limits

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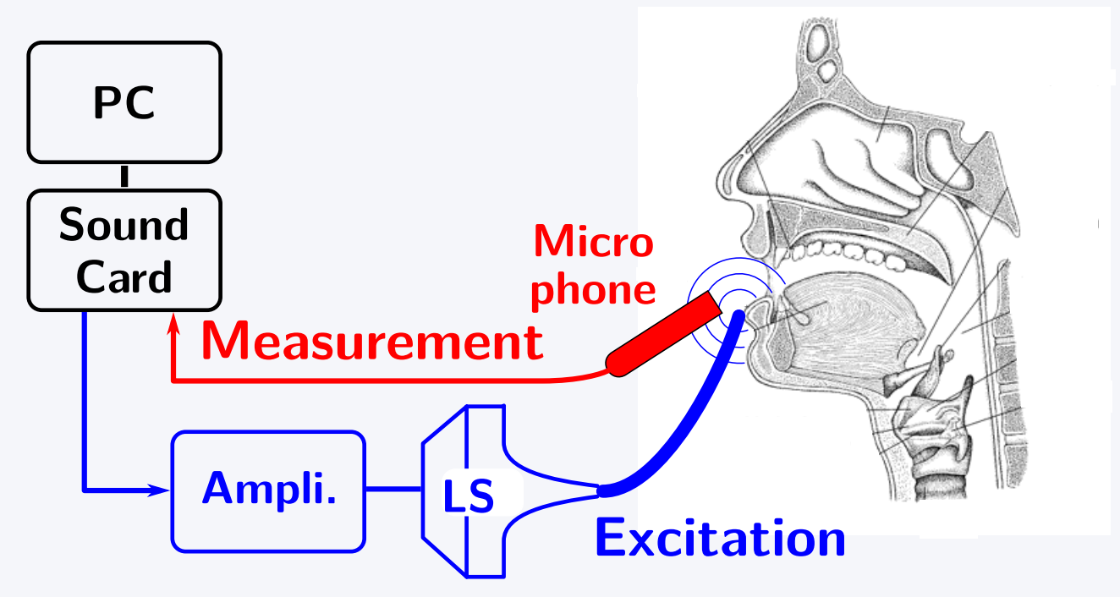
Context and objectives

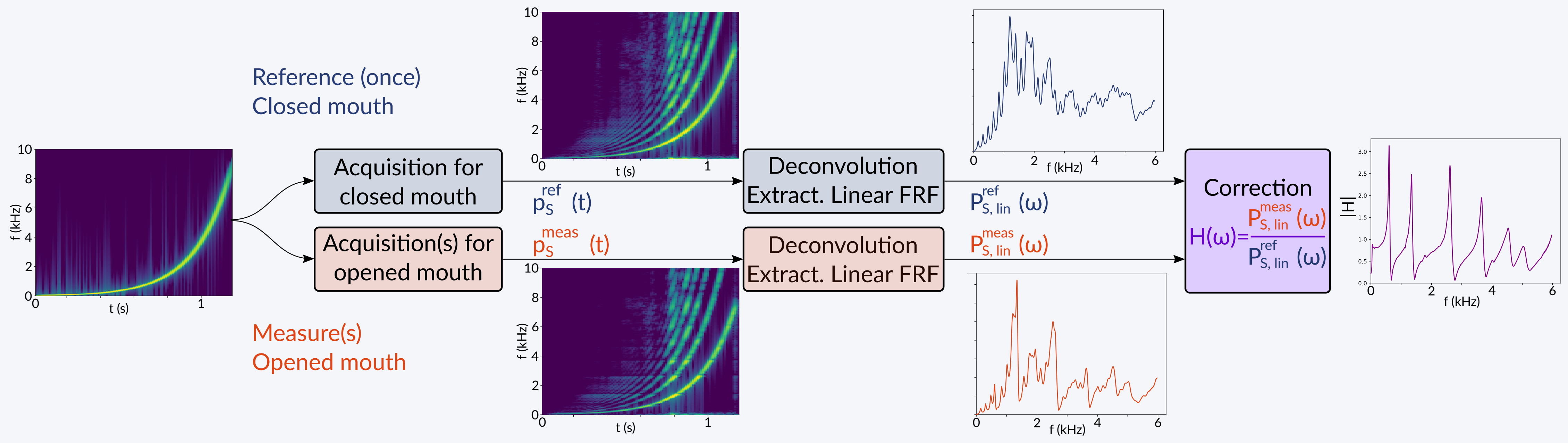
Non-invasive techniques (such as the so-called RAVE [1]) were developed to characterize vocal-tract acoustics using a **broadband excitation and a microphone positioned closed to the lips**. The measured pressure for an open-mouth condition, calibrated by a mouth-closed reference condition, provides estimates for the **resonance frequencies of the radiating vocal-tract**. Recently, sweep-based methods were reported to measure vocal-tract impedance at the lips [2, 3], with an improved accuracy of the resonance frequency, and the possibility to work on amplitude and phase of measured quantities. We focus here on the **unvoiced case**.
Objectives: highlight the **underlying hypotheses** of impedance measurements at the lips, and test their **validity domain**.

Testbed

Measurements made on idealized vocal tract:
open-closed cylinder
length $L_{VT} = 15$ cm
diameter $d_{VT} = 21$ mm



Measurement principle and sweep parameters



Impulse responses measurements for non-linear system [4]:

1. exponential **sweep excitation** (1 s, 100 − 6000 Hz)
2. convolution with inverse sweep to recover **linear response**
3. steps 1. and 2. carried out once for closed-mouth condition as **reference**, then for open-mouth condition as operational **measurements**
4. **correction**: measured spectrum divided by reference spectrum $H = P^{meas}/P^{ref}$

Measurement model

Radiation coupling theory [5] between vocal tract (VT) and excitation tube (S).

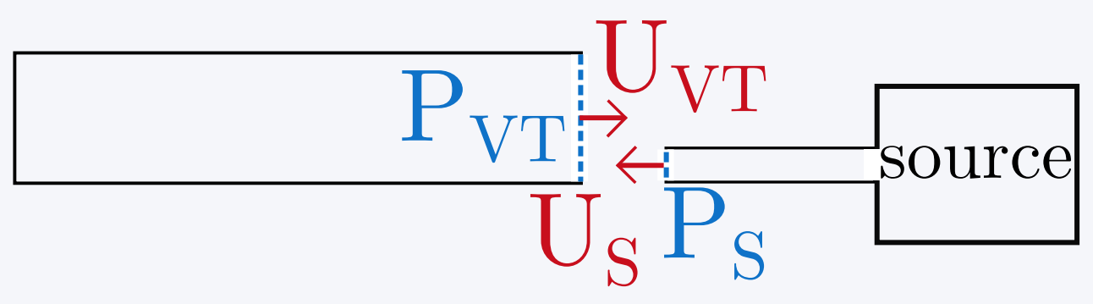
$$\begin{pmatrix} P_S \\ P_{VT} \end{pmatrix} = \begin{pmatrix} Z^{ref} & Z_m \\ Z_m & Z_R \end{pmatrix} \begin{pmatrix} U_S \\ U_{VT} \end{pmatrix} \qquad (1)$$

$$H = \frac{P_S^{meas}}{P_S^{ref}} = \frac{Z^{meas}}{Z^{ref}} \frac{U_S^{meas}}{U_S^{ref}} \qquad (2)$$

With following **hypotheses**, one can lead to:

$$\boldsymbol{H = \frac{P_S^{meas}}{P_S^{ref}} = \frac{Z_{VT}}{Z_{VT} + Z_R}} \qquad (3)$$

Z_m mutual impedance
Z_{VT} vocal tract input impedance seen from the lips ($P_{VT}^{meas} = -Z_{VT} U_{VT}^{meas}$)
Z_R vocal tract radiation impedance



Resonances of radiating vocal tract:

$$\boldsymbol{Z_{VT} + Z_R = 0} \qquad (4)$$

Uniform pressure between vocal tract and excitation tube

Hypothesis: lips and excitation output are close enough, so that pressure at the lips is the same as the pressure at the excitation output.

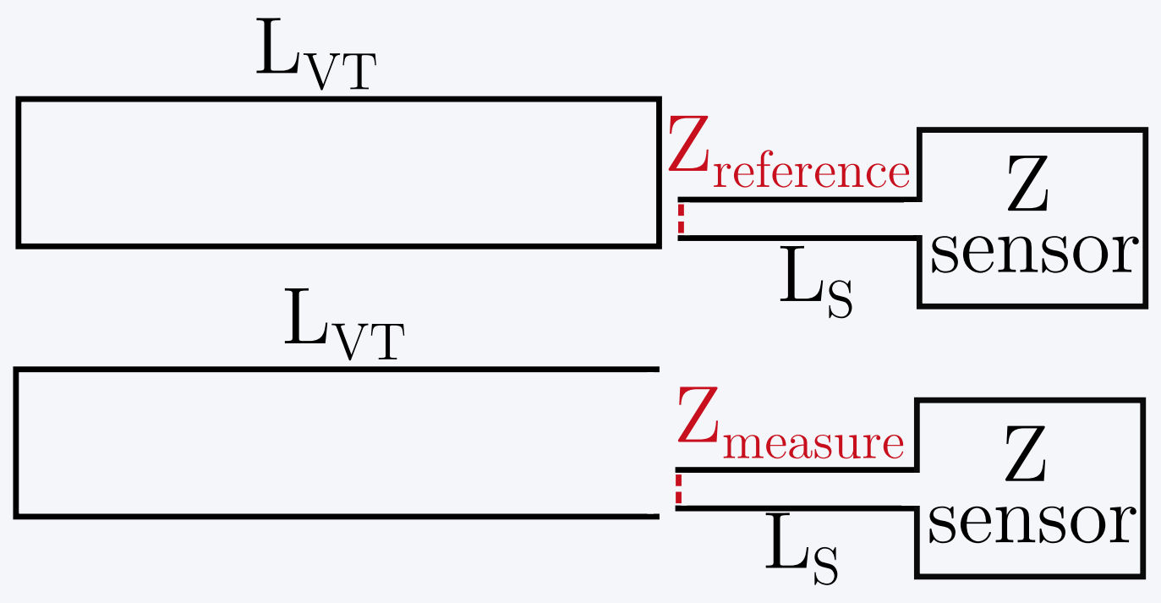
$$\boldsymbol{P_{VT} = P_S} \Rightarrow \frac{Z^{meas}}{Z^{ref}} = \frac{Z_{VT}}{Z_{VT} + Z_R} \qquad (5)$$

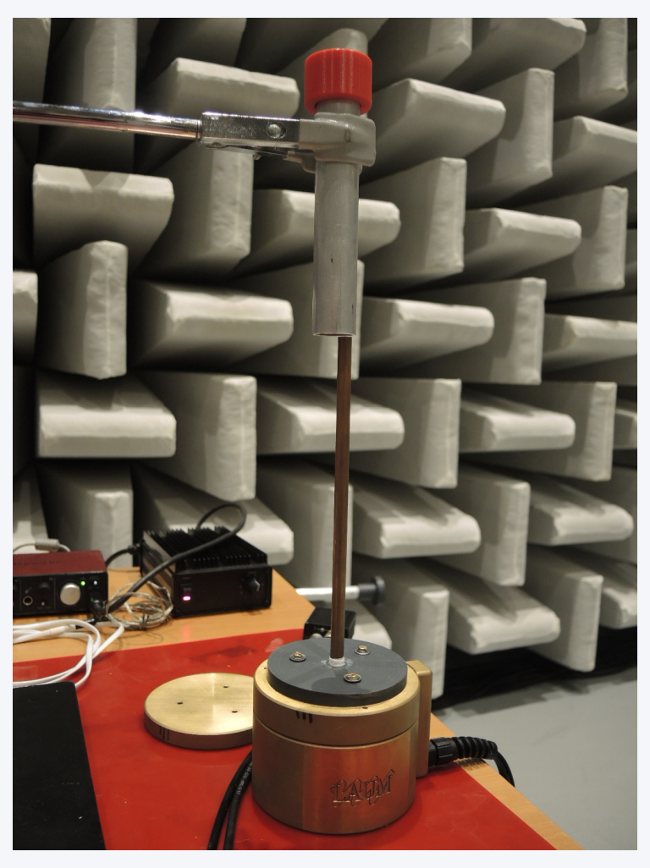
Method: comparison between

$\frac{Z_{VT}}{Z_{VT}+Z_R}$ from **analytical expressions** for Z_{VT} and Z_R;
$\frac{Z^{meas}}{Z^{ref}}$ from Z^{ref} (for closed mouth condition) and Z^{meas} (opened mouth) measured by the **impedance sensor** [6] and evaluated at the exit section of the excitation tube.

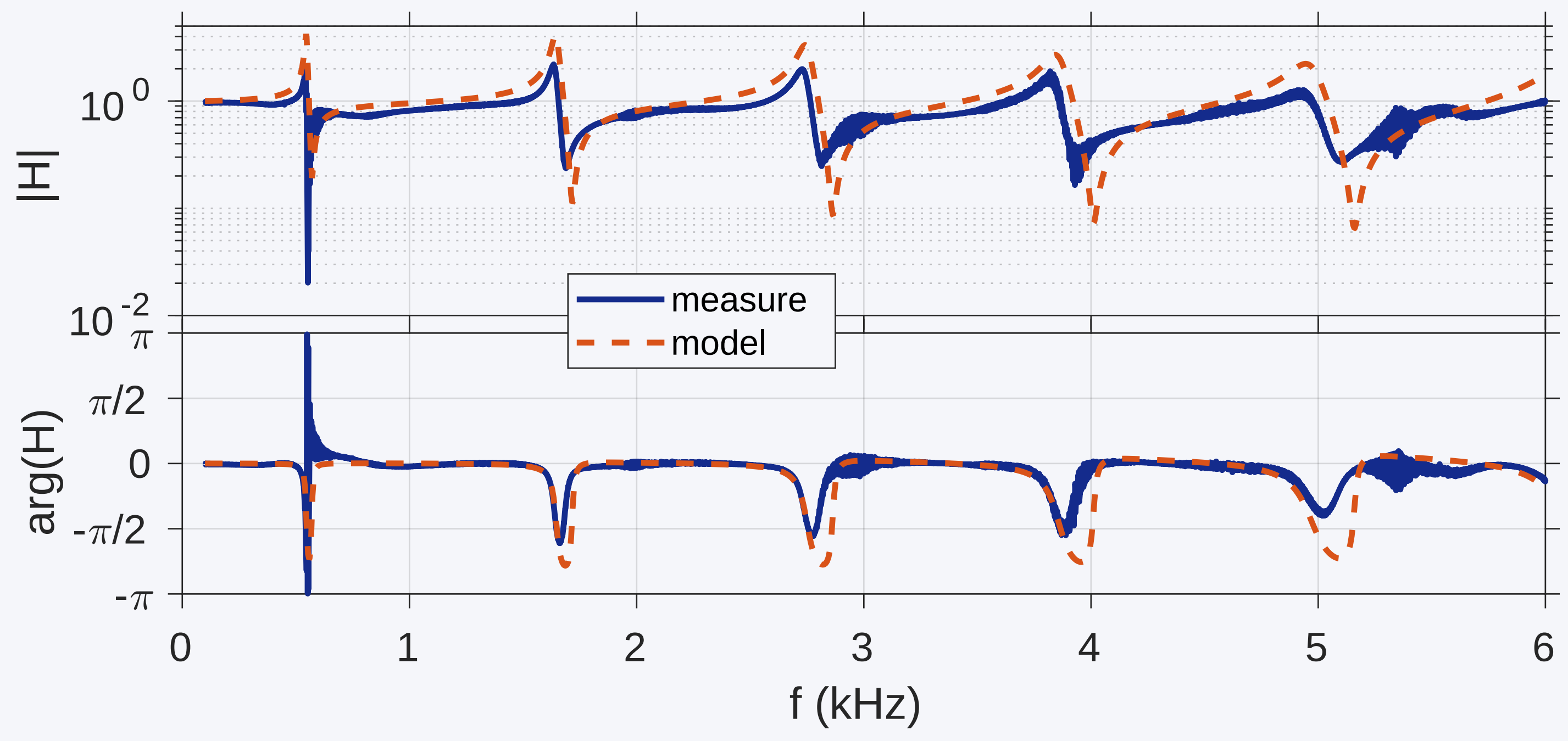
Impedance sensor measurements :

- **excitation tube**: cylinder $L_S = 20$ cm, $d_S = 6$ mm
- provide reduced impedance at capillary output (radiation impedance)





Results: average relative errors on resonance frequencies $\simeq 0.6\%$, on quality factors $\simeq 20\%$.



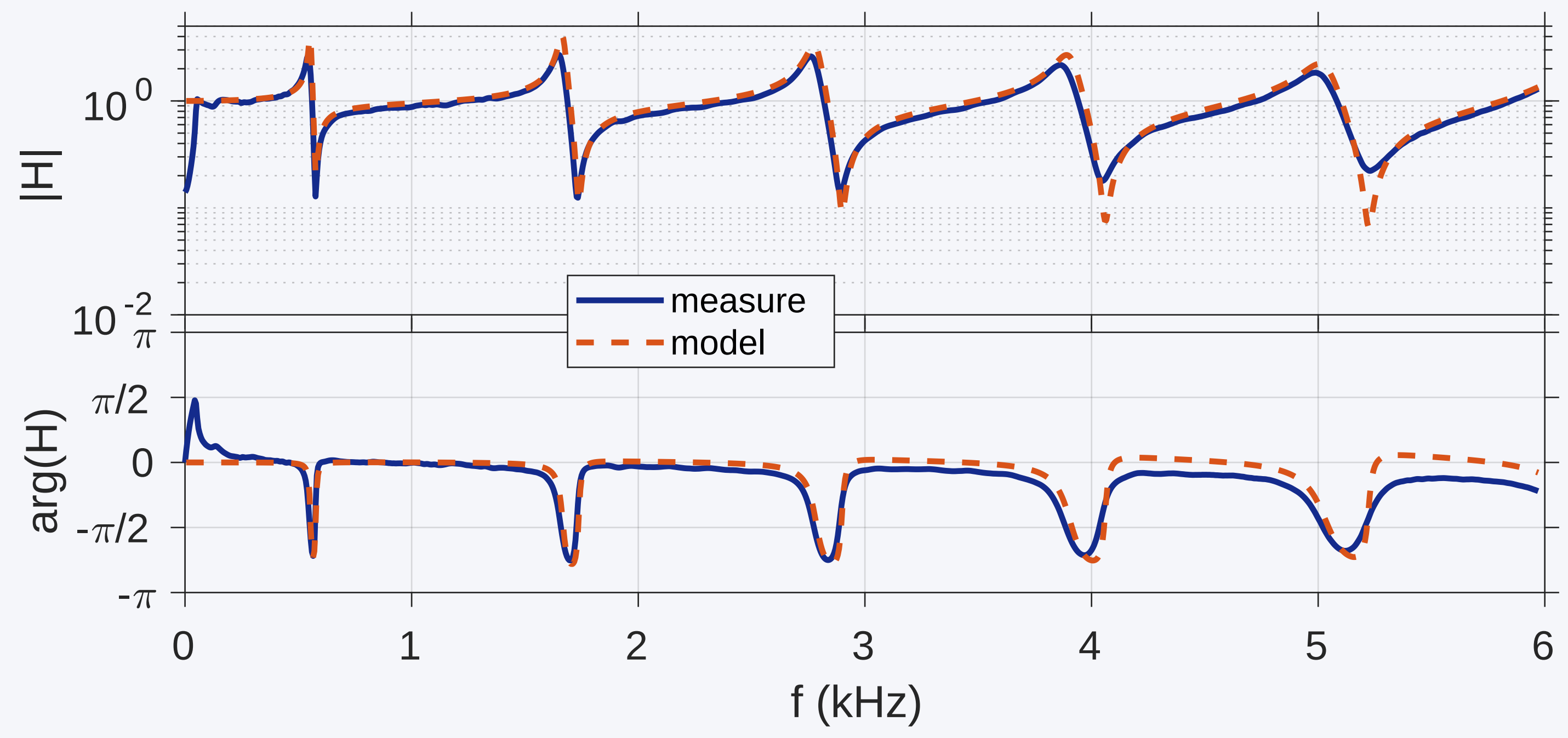
Ideal acoustic flow rate source

Hypothesis: the excitation output is small enough, so that the acoustic flow rate U_S does not depend on the load (i.e. open or closed vocal tract).

$$\boldsymbol{U_S^{meas} = U_S^{ref}} \Rightarrow \frac{P^{meas}}{P^{ref}} = \frac{Z_{VT}}{Z_{VT} + Z_R} \qquad (6)$$

Method: comparison between pressure measurements at the lips with sweep excitation principle of ratio $\frac{P^{meas}}{P^{ref}}$ and analytical computing of $\frac{Z_{VT}}{Z_{VT}+Z_R}$.

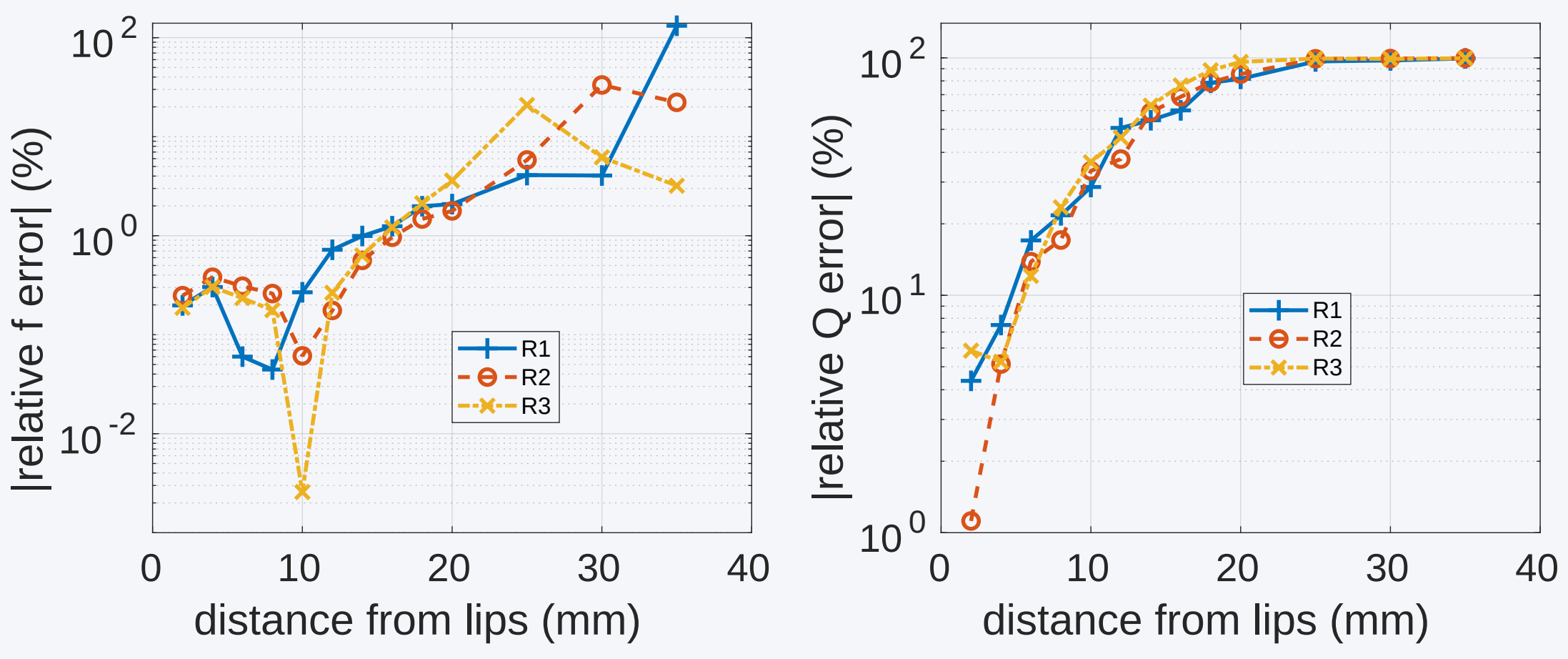
Results: average relative errors on resonance frequencies $\simeq 0.4\%$, on quality factors $\simeq 23\%$.



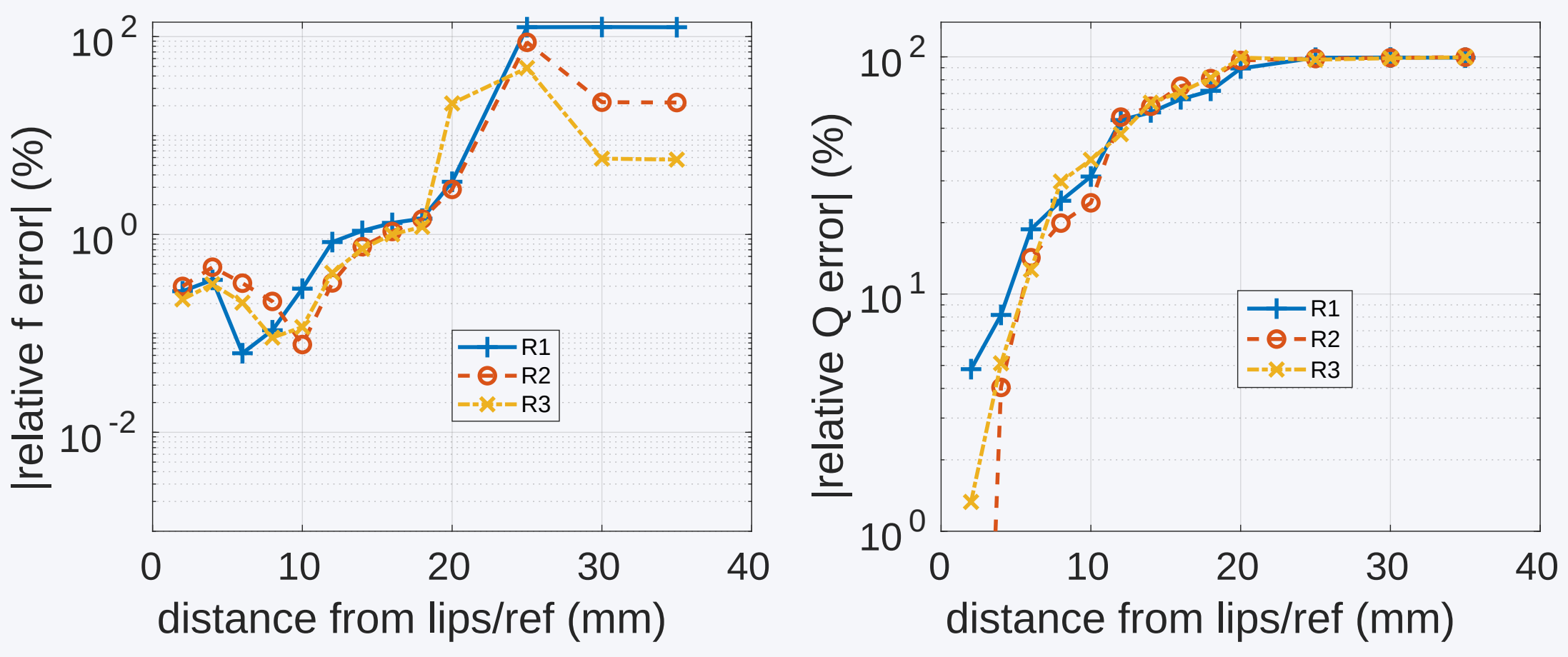
Robustness with distance from lips

Method: moving horizontally away excitation tube and microphone from the inlet, and computing frequency and quality factor ratio errors (to distance $= 0$) for the first three resonances ($R_{1,2,3}$).
Results:

1. One reference and one measurement for each distance: **pressure hypothesis $P_{VT} = P_S$ limit**.



2. Only one reference at lips (0) and measurements for each distance: **robustness to shifts** between reference and measurement.



- resonance frequencies relative errors: $< 1\%$ for distance < 15 mm
- quality factors relative errors suffers from distance: $> 10\%$ for distance > 5 mm

References

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[6] Dalmont & Le Roux, JASA, 123(5) :3014-3014, 2008.

Conclusion and perspectives

- pressure ratio at the lips H → radiating vocal tract
- good correlation measurements vs numeric computation
- highlight uniform pressure on lips plan and ideal flow rate source
- robust access to resonance frequencies for distance from lips < 2 cm
- quality-factor estimate suffers from proximity between maxima and minima in pressure ratio
- errors from long-range inefficient acoustic coupling
- need for exploring case with voice source

12th International Conference on Voice Physiology and Biomechanics, Grenoble, 2020

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