Evaluation of the acoustic and aerodynamic constraints of a pneumotachograph for speech and voice studies

Alain Ghio, Bernard Teston,

Laboratoire Parole et Langage

UMR 6057, Université de Provence - CNRS, 29 avenue Robert Schuman, 13621 Aix-en-Provence cedex 1, France

Tel: +33 (0)4 42 95 36 30 Fax: +33 (0)4 42 59 50 96

Email: alain.ghio@lpl.univ-aix.fr, bernard.teston@lpl.univ-aix.fr , http://www.lpl.univ-aix.fr

ABSTRACT

To measure oral and nasal airflow during speech production, several conditions must be gathered. In this aim, we designed and built a pneumotachograph with particular care to optimise its response time, linearity and acoustical response. This flow meter is based on the grid flow meter principle with a small dead volume and specific linearization for the inhaled and exhaled airflow. A soft silicone rubber mask, pressed against the speaker's face prevents air leakage, without hindering articulatory movements. The acoustical distortions of the speech sound through the device are remedied by an adapted signal processing from its transfer function.

1. INTRODUCTION

The measurement of the aerodynamic parameters for the study of the articulatory mechanisms in the speech and voice production, particularly that of the oral and nasal flows examination, presents several problems which were never solved other than by compromises. To measure the air flow, a certain number of conditions must be joined together:

1- The flow meter must be bidirectional (inhaled and exhaled airflows).

2- Thermodynamic conditions of the air (temperature, composition, moisture) should not have effects to the measures.

3 - Turbulences with the lips (which depend on the type of phoneme) should not disturb measurements.

4- The dead volume of the sensor must be as small as possible to obtain a low acoustic distortion and a good response to fast variations of flow (especially for the oral air flow).

5-The flow meter should not have a resistance to the air flow likely to disturb the operation of the vocal tract.

6-The flow meter must be correctly adapted to the anatomy of the speaker to avoid leakages, source of errors of measurement, without obstructing the articulatory movements.

7- The device must be compatible with the hospital standards hygiene conditions.

It is very rare, in instrumentation, to meet a sensor which satisfies so many contradictory conditions. Some of them were already posed for measurements on breathing and quite naturally, phoneticians used sensors of respiratory flow (pneumotachographs) associated with anaesthesia masks, with not very reliable results, because these devices were very badly adapted to the dynamics of the speech production. In spite of this projection, very few systems were worked out for the articulatory studies. To equip the EVA2™ system (SQLab, www.lpl.univ-aix.fr/~sqlab), we produced an airflow sensor matching the main part of the conditions developed previously. The object of this study is to evaluate and correct the acoustic and aerodynamic distortions generated by this device.

2. PNEUMOTACHOGRAPHS

The pneumotachographs or PTG are sensors of air flow which measure the gaseous exchange in breathing. A good linearity was the main challenge for a long time. This quality was reached satisfactorily only by Fleisch [Fle25], whose PTG had a great dead volume and a significant resistance to the flow. To reduce this last disadvantage, Lilly [Lil50] proposed the first PTG with grid whose various evolutions were used for many phonetic studies in particular by Guilbert [Gui73]. Rothenberg [Rot77] was the first of the rare attempts to carry out a PTG adapted to the particular constraints of aerodynamic measurements in speech production. With an aim of solving the problem of the response time of the PTG, he integrated the grid of measure to the walls of an anaesthesia mask. Always diffused, this system cannot really be regarded as a precise flow meter of measurement. Other principles of PTG were proposed such as those with hot wire or Doppler effect by ultrasounds [Bue86], but they appeared incompatible with certain conditions developed in the introduction.

2.1 The aerophonometer

The PTG we study derives directly from the principle described by Teston [Tes87, Tes93]. Taking into account the specificity of its application and its realization, we baptized it "aerophonometer" to differentiate it from the standard PTG. This device is a PTG with grid (stainless steel wire of 200 µm diameter and a step of mesh of 250 µm), of size reduced (30 mms diameter and 20 mm length) to optimize its response time and its linearity in all the articulatory contexts. Thanks to its association with differential pressure transducers (Data Instrument DCXL) very sensitive and stable, it is able to apprehend a flow of the order of one cm3/s. The resistance of the grid is 10 Pa by dm3/s (litre/s), i.e. approximately 1% of the intra oral pressure of a normal subject, which does not disturb the operation of the vocal tract. Resistance was selected for a level of saturation of the sensor to the value of 10 dm3/s in forced breathing. These values represent a dynamics of 60 dB. To reduce the non-linearity of measurement caused by aerodynamic turbulences produced during speech production, the pressure tap is made in 8 points of the circumference of the measurement pipe and a grid of tranquillization (negligible in resistance) is laid out in front of the pressure taps. The sensor is made with synthetic material (Polyacetal) which has a very good mechanical resistance to sterilization and UV.

2.2 Adaptation to the anatomy of the speaker

This type of flow meter equips the system EVA2 ™ (Computerised Vocal Assessment, SQLab) which is a device designed for the recording and the study of many parameters of the speech and voice production: sound, pitch, intensity, airflows, pressures [Tes95]. The simultaneous recording of the sound and the airflows to the mouth and the nostrils requires the use of a "mouthpiece" which is a mechanical stand of the microphone, sensors of flow and flexible silicone mask allowing the sealing necessary to the reliability of measurements of oral air flow (Fig 1). The nasal sensor is located under the oral sensor and vertically to follow the natural flow of the air to the nostrils. The flexible silicone masks, of a pleasant contact on the skin, take support on the speaker's face by releasing the nose and by taking the chin. They allow normal movements of the mandible in current speech, while preserving an excellent sealing. They are also easily sterilizable.

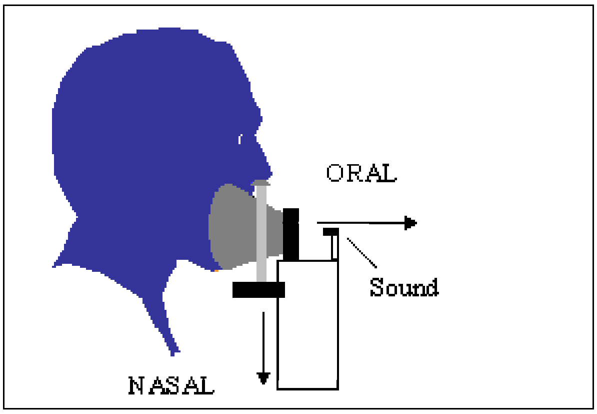

Fig 1. Speaker position with aerodynamic sensors.

3. LINEARIZATION OF AIRFLOWS MEASUREMENTS

3.1 Position of the problem

The principle of measurement of the flow by a PTG consists in opposing a resistance to the air flow and to measure the pressure difference ΔP before and after. It varies according to the speed of the fluid, i.e. its volumic flow D. For low values, the flow is laminar. The laws of the mechanics of the fluids show that, in this case, $\Delta P = R.D$ where R is resistance (equation of Poisseuille). For more significant values of flow, it becomes turbulent. The pressure loss ΔP is then proportional to the square of the flow (law of Venturi): $\Delta P = R.\ D^2$.

In a general way, the relation between these values is formalized by: $\Delta P = R.\ D^N$.

The precise knowledge of the relation between ΔP and D makes it possible to bring back the measurement of flow to a measurement of differential pressure, operation technically easy to realize. Indeed, ΔP can be easily measured by differential pressure sensors. Those deliver a tension V proportional to ΔP. If the device is regulated in order to give a tension V_{calib} for a flow gauged D_{calib}, the measurement of the flow will be finally equal to:

$$(Eq.1) \quad D = G\sqrt[n]{V} \text{ où } G = \frac{D_{calib}}{\sqrt[n]{V_{calib}}}$$

By applying a logarithmic transformation, we obtain:

$$(Eq.2) \quad Log(D) = Log(G) + \frac{1}{n}Log(V)$$

which translates a linear relation $y = a.x+b$ *(Eq.3)*

where $y = Log(D)$, $x=Log(V)$, $a=1/n$, $B = Log(G)$

Our objective is to obtain empirically the parameters a and b from experimental measures (Fig 2) .

3.2 Measurements

The chain of instrumentation is composed of a blower which provides an adjustable and regular flow. This air flow is controlled by flow meters of high degree of accuracy TSI ™ model 4040 (for the flows from 0 to 5 dm^3 /s) or model 4140 (from 0 to 0.33 dm^3 /s). The air flow thus gauged is sent in the sensors whose output voltage is measured by a Fluke 45™ multimeter. A microcomputer PC controls the chain of instrumentation and records, via two ports series (RS232), the values provided by flow meter TSI ™ and the voltmeter. The oral flow sensor is not geometrically symmetrical because of the grid of tranquillization which has a significant effect. Also, measurements were carried out with blown and aspired air flows. This dissymmetry is marked for the sensor of nasal flow because of the air intake to the nostrils.

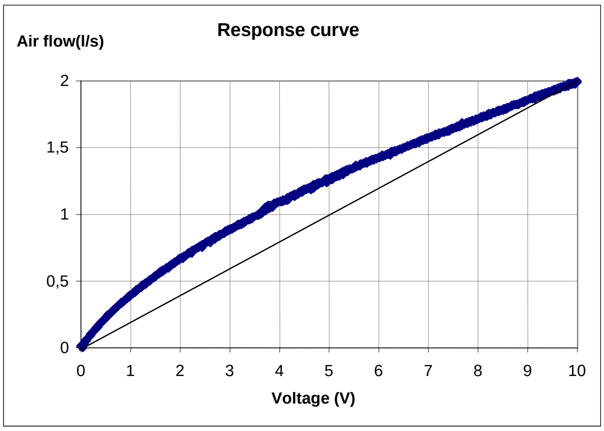

Fig 2 Pneumotachograph response curve of the expired oral air flow (for the range 2 dm^3/ s max)

3.3 Results

A linear regression carried out to the logarithmic measures (cf Eq. 2) allows us to obtain the factors A and B of Eq.3. Thus, for the flow of expired oral air (range 2 dm^3 / S max), the measurement of the flow is obtained by the relation: $D\ (in\ dm^3/s) = 0.4436.\ V^{0.654}$ where V is the tension in volts at exit of the sensors.

For values of low flow, the relation is linearised and tended towards a relation where $D\ (dm^3/s)$ is locally proportional to the difference in pressure.

The adjustment of the function of correction for the flows inspired and expired with the mouth and the nostrils made it possible to obtain, in all the ranges of measurement, a linearity of the sensors corrected about 1%. The precision is validated by volumetric measures with a syringe-standard of 3 liters (series 5530, Hans Rudolph Inc, the USA) for various rates of flow. Air volume is obtained by a temporal integration of the air flow signal.

Drift is another source of nonlinearity for such a sensitive sensor. The pressure sensors we use have a weak drift in temperature and it is useless to control it. However, an automatic reset is made before each recording to cancel this problem.

4. RESPONSE TIME OF THE FLOW METERS

4.1 Position of the problem

Response time of the flow meter is related to the phenomena which can delay the measure of a fast variation of flow. This delay is linked to the response time of the sensor or to its bandwidth in frequency. But the main cause of this delay is the dead volume of the flow sensor, great defect of the PTG based on respiratory measurement. The aerophonometer was built for that, with a geometrical volume of 8 cm3 and with very short pipes connections to the pressure sensors. These transducers (series DCXL, Data Instruments) have response times quite lower than 1 ms. The delay is also a function of the filtering applied to the signal of the flow before analog-to-digital conversion. Indeed, the fast and sensitive pressure sensors behave like poor microphones and can record the variations of acoustic pressures. To avoid aliasing, we use a 8th order low pass Bessel filter with a cut-off frequency to 60 Hz. The indicial response of this function has no delay and bounce. So, it is well adapted to this use.

4.2 Measurements

To test the response of the flow meters, we produce an impulse of air flow thanks to a weight falling on an air bag. The noise of the shock is collected by the microphone of the mouthpiece and gives the precise moment of the beginning of the flow transient.

The total response time of the system is illustrated in figure 3 for the oral sensor. It is lower than the millisecond. The nasal sensor was optimized less in the plan of dead volume (tubes of 12 cm, Fig 1). Its response time is about 2 ms.

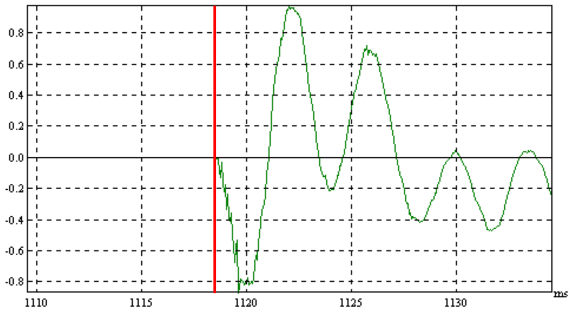

Fig 3a: Acoustic signal of the shock

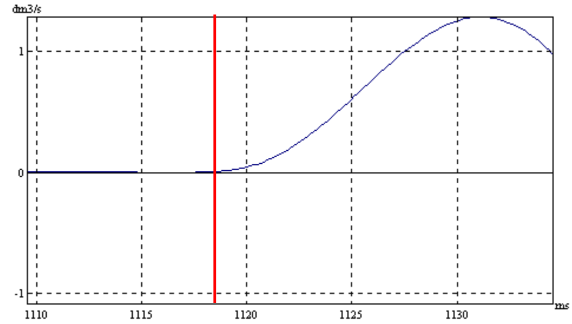

Fig 3b: Establishment of the oral air flow

5. HARMONIC RESPONSE OF THE MASK-SENSOR UNIT

5.1 Position of the problem

The flow sensor, placed in the prolongation of the vocal tract, introduces a distortion of the speech sounds according to its own transfer function. Even if the measurement pipe is reduced to a minimum, it has a certain volume increased by the volume between the mask and the speaker's face. Additional cavities with the measurement pipe linked to the pressures sensors can also produce parasitic acoustic phenomena. Lastly, the device disturbs the natural acoustic radiation with the lips. In spite of the application of all the fundamental principles to avoid acoustic distortions as much as possible, there are always some which are necessary to correct.

5.2 Measurements

We measure the harmonic distortions of the mask-sensor thanks to an artificial head loudspeaker, designed for this use, under conditions identical to the use of the system (Fig 4). The signal source is provided by a white noise generator (Brüel & Kjaer model 1027). The recordings are carried out in soundproof room. Fig 5 represents the difference between the long-term spectrum of the response of the system and that of the artificial head.

Fig 4 Artificial head loudspeaker to study acoustic distortion

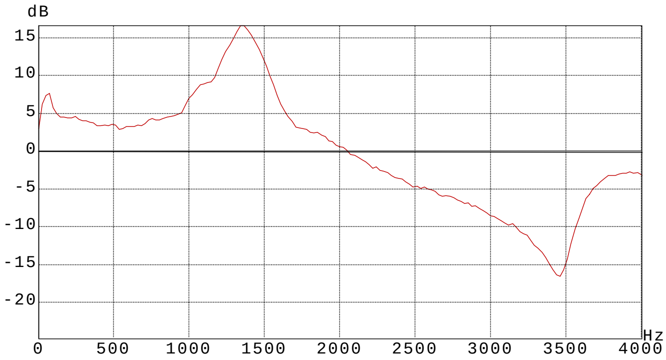

Fig 5 Transfer function of the mask-sensor

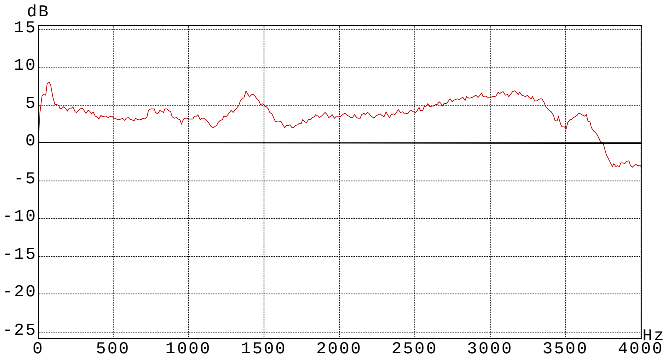

Fig 6 Transfer function corrected

It is noted that the mask-sensor unit behaves like a low-pass filter with a strong resonance towards 1.4 kHz caused by the additional cavity between the lips and the grid. The anti-resonance located at 3.5 kHz on the spectrum is probably the acoustic consequence of the side cavities of measurement pipe which collect each one 4 points of measurement of pressure. Their volume is about 1 cm3 and cannot be absorbed because of hygiene requirements (the sensor must be able to be sterilized easily). The corrections we do consist in applying, by digital filtering, an equalization whose frequential profile is the reverse of the transfer function of the system. The result of the correction is presented in Fig 6

CONCLUSION

This work of optimal devices adapted to speech production studies requires the realization of specific instruments of calibration as well as a constant rigour and a determination. Although satisfied of the general performances of the device, we consider in a future immediate to perfecting the whole system and, more particularly, the correction of the acoustic distortions.

BIBLIOGRAPHY

[Fle25] Fleisch A. (1925), "Der Pneumotachograph; ein Pageantry zur Geschwindigkeits-registrierung der Atemluft ", Pflugers Arch. Ges. Physiol., vol. 209, pp. 713-722

[Tes93] Teston, B (1993), "A new airflowmeter design for the investigation of speech production. Proc. Eurospeech 3, ISCA, Berlin, 405-409.

[Lil50] Lilly J.C. (1950), "Flowmeter for recording respiratory flow of human subjects", Methods in Medical Research, Flight 11, pp. 113-121

[Gui73] Guilbert H.R. (1973), "Oral airflow during stop consonant production", Folia Phoniatrica, vol. 25, pp. 288-301

[Rot77] Rothenberg Mr. (1977), "Measurement of airflow in speech", J Sp. Hear. LMBO, vol. 20, pp. 155-176

[Bue86] Buess C, Pietsch P., Guggenbuhl W, Koller E.A. (1986), "Design and construction of has pulsed ultrasonic air flowmeter", IEEE Trans. Bio-Med. Eng., Flight Bme-33, No 8, pp. 768-774

[Tes87] Teston B. (1987), “Etude d'un aérophonomètre de grande dynamique et faible constante de temps”, 16èmes JEP, GALF, Hammamet, pp. 132-135.

[Tes95] Teston B, Galindo B (1995), "A diagnosis and rehabilitation aid workstation for speech and voice pathologies". Eurospeech 4, ESCA, Madrid, pp., 1883-1886.