First International Conference on
Spoken Language Processing (ICSLP 90)
Kobe, Japan
November 18-22, 1990

MEASUREMENT OF SOUND WAVE CHARACTERISTICS IN THE VOCAL TRACT

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ABSTRACT

In this paper the characteristics of sound pressure distribution in the vocal tract are described on the basis of acoustic measurement. The measurement was performed with plaster replicas of the oral cavity. The validity of plane wave propagation is examined from the measured spatial distribution of the amplitude and phase of sound pressure for pure tone. It is shown that at certain frequencies, there exist points where sound pressure is absolutely zero, with the phase spatially circulating around them. A simple model is considered to explain this phenomenon. And up to about 4kHz except at these certain frequencies, the wave front is almost 1-dimensional though an amplitude gradient can be seen in the vertical direction. This paper also presents the characteristics of particle trajectories and of sound intensity fields.

1. INTRODUCTION

A physical model of the vocal tract has been constructed previously as a cascade connection of acoustic uniform tubes in which the propagation of plane waves is assumed. This assumption is based on the fact that the wavelength of sound at the frequency range of speech is relatively long compared with the representative size of the cross section of the vocal tract. The distribution of sound pressure in the vocal tract model has been studied[1], and pressure measurement in the real vocal tract has been performed[2-4]. However, sound wave characteristics have not been discussed sufficiently on the basis of detailed 2 or 3-dimensional measurement. The real vocal tract has complicated shape and local reflection of sound may occur at any point. For the improvement of the vocal tract model so as to better explain the actual speech production process, it is necessary to investigate the characteristics of sound waves in the real vocal tract.

In this paper we show measurement data of the sound pressure distribution in the oral cavity and around the lips. And the validity of plane wave propagation is examined by the experimental results. Since it is very difficult to directly measure the sound pressure distribution, we made plaster replicas by using impression material, which duplicates the actual shapes of the oral cavities and the lips, and measured the spatial distribution of the amplitude and phase of sound pressure in the replicas for pure tone. Two-dimensional measurement was performed on vertical and horizontal planes in the replicas. A probe microphone installed on a movable stage is used to pick up the sound pressure at the specified position in the replicas.

As a result it is shown that at certain frequencies, though the radiation load at the lips is resistive, there exist points where sound pressure is absolutely zero, with the phase spatially circulating around them. The circulation of phase is essentially 2 or 3 dimensional, and the well-known 1-dimension model cannot simulate these phenomena. A simple model is considered to explain these phenomena. And up to about 4kHz, except for those points mentioned, phase contours on the vertical and horizontal measurement planes are aligned in the anterior-posterior direction, so that, as a rough evaluation we can consider that the wave front is almost 1-dimensional, though an amplitude gradient in the vertical direction is seen at the region around the tongue tip. We can also compute the distribution of particle velocity, trajectory, and sound intensity fields from the measured sound pressure distribution. The characteristics of these physical quantities are also presented in this paper.

2. MEASUREMENT EQUIPMENT

2.1 Experimental setup

Fig.1 shows the block diagram of the measurement system. The replica is placed in a plane baffle. A uniform acoustic tube (area 5.5 cm^2) is connected to the replica and a speaker is attached at the end of the uniform tube. The speaker is driven by pure tone from a frequency response analyzer. The amplitude and phase of sound pressure in the replica is picked up by a condenser microphone, Mic.#2, which is attached to a pole on an XY pulse stage. A probe tube for Mic.#2 is made of glass, with a diameter of 3.0 mm and a length of about 40 cm. A signal from Mic.#1, whose location is fixed at 100 mm distant from the replica-side end of the uniform tube, is used as a reference signal; the amplitude and phase in the replica are measured relative to this reference signal. Typical errors of the analyzer are 0.03dB and 0.05 degrees. The analyzer and the pulse stage are controlled by a minicomputer. The required time for measurement at one point is about 6 seconds including movement time.

2.2 Replicas of oral cavities

Since it is very difficult to directly measure the sound pressure distribution in a real vocal tract, we made replicas duplicating the actual shapes of the oral cavities and the lips. Alginate impression material was used to obtain molds of the oral cavities together with the lips, and the replicas were formed with plaster. Two replicas (called Replica(I) and Replica(II)) were made with the articulation of /a/. For the facilitation of measurement, the articulation is somewhat enhanced by lowering the mandible. Though the replicas do

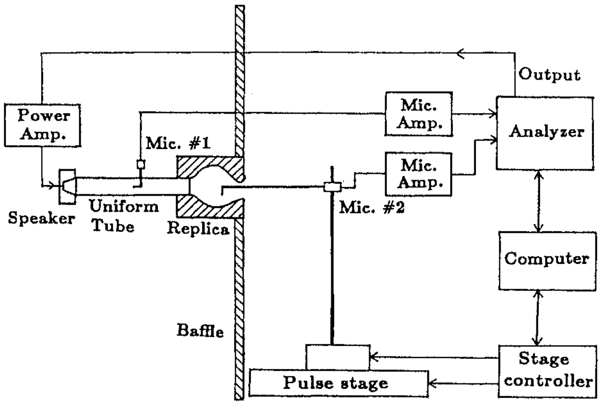

Fig.1 Block diagram of measurement system.

not include the pharynx, the distribution of sound pressure can be examined since Thevenin's equivalent sound source can be considered to exist at the junction between the replica and the uniform tube, and the properties of the sound source do not affect the characteristics of the sound pressure distribution except for its absolute amplitude and phase. The relative distribution of sound pressure is sufficient to investigate the acoustic characteristics of the oral cavity.

3. EXPERIMENTAL RESULTS

3.1 Sound pressure distribution

Vertical plane in Replica (I)

Fig.2 shows amplitude and phase contours of sound pressure on the vertical plane (midsagittal plane) of Replica(I). Upper and lower solid lines in each chart are the outlines of the replica wall. Measuring frequencies are from 2.0 to 6.0 kHz and contour steps are specified in each chart. The values of the amplitude and the phase are relative to those of the farthest point from the lips. In the frequency of 2.0 kHz, although the contours are not exactly straight, we can consider that both the amplitude and phase contours are aligned in the anterior-posterior direction; i.e. the sound wave is almost 1-dimensional. It is noted, however, that amplitude is relatively high at the lower region between the tongue tip and lower lip. In the charts for 3.0 and 4.0 kHz, the phase contours are deformed much more; but with rough evaluation, the phase characteristics of the wave can be regarded as 1-dimensional. The amplitude contours, however, show that sound pressure at the anterior bottom of the oral cavity becomes high and an amplitude gradient exists in the vertical direction. The maximum difference of the amplitude in the vertical direction is 3.3 and 4.1 dB at 3.0 and 4.0 kHz respectively. In the frequencies of 5.0 and 6.0 kHz, both amplitude and phase contours are no longer 1-dimensional. It is clearly seen that the amplitude decreases extremely at the region above the tongue tip, and phase contours circulate spatially around the center of the amplitude decrease. Since the phase becomes discontinuous at the center of the amplitude decrease, the amplitude must be absolutely zero at this center. Although we cannot measure this zero pressure because of the size of the probe tube and the small leakage of sound through the wall of the probe tube, we can judge from the measured phase circulation that there is a point where the sound pressure is zero. It should be noted that zero pressure does not imply the vanishing of the sound wave because particle velocity does not become zero at the point of zero pressure. A simple model for the occurrence of this peculiar point is described later.

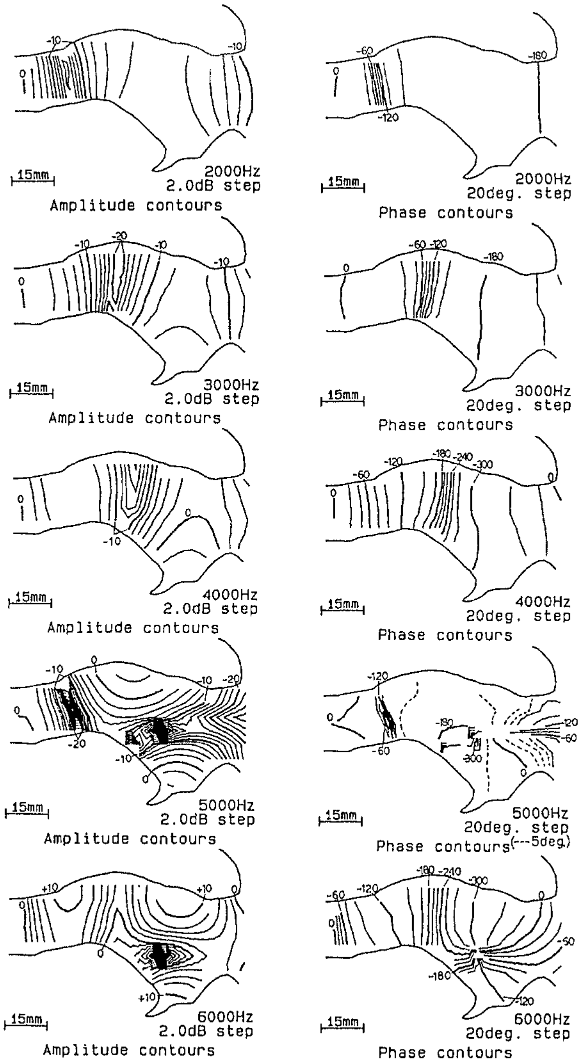

Fig.2 Amplitude and phase contours (vertical plane of Replica(I)).

Vertical plane in Replica(II)

Fig.3 shows amplitude and phase contours on the vertical plane of Replica(II). Measurement frequencies are 2.0, 3.0 and 5.6 kHz. Though the vertical figuration of Replica(II) is somewhat different from that of Replica(I), the characteristics of the distribution of sound pressure and their tendency to change with respect to the frequencies are similar to those of Replica(I).

Horizontal plane in Replica (II)

In the lower frequencies below about 1 kHz, both the amplitude and the phase distribution is almost constant regardless of the measurement position except at the mouth region where the amplitude of sound pressure decreases due to sound radiation. At 1.0 kHz, the phase difference between the lips and the hindmost point of the replica (distance is almost a quarter of the wavelength) is about 10 degrees. In the frequencies above about 1.6 kHz, a node of the standing wave appears in the oral cavity. Fig.4 shows amplitude and phase contours on a horizontal plane of Replica(II) which was determined by sight as the plane located at the mid height

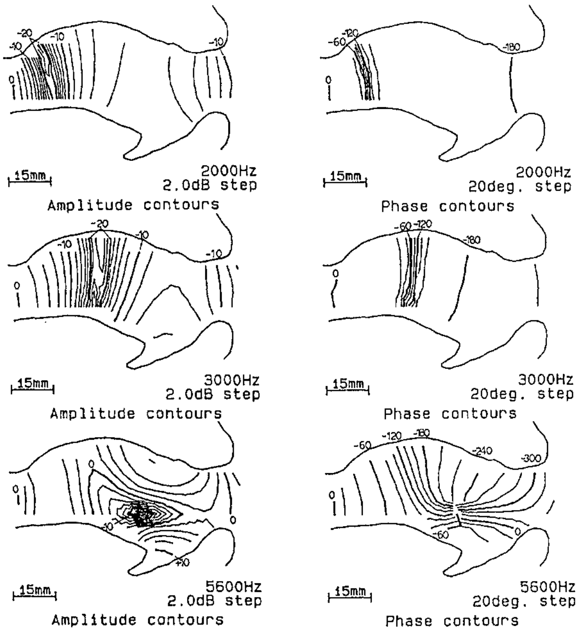

Fig.3 Amplitude and phase contours (vertical plane of Replica(II)).

between the upper and lower dental arcs. Upper and lower solid lines in each chart are the left and right outlines of the replica cheek respectively, and the right opening is the mouth of the replica. At 2.0 kHz, the spatial phase change occurs mainly at the position of this node as the radiation impedance is small and the sound wave is reflected at the lips (magnitude of reflection coefficient calculated from equivalent circular piston model[5] is about 0.82). It is seen that the contours become arc shaped at the region where the wall expands, and the sound wave travels along the wall. Similar results are obtained at 3.0 kHz except that the intervals between contours become longer due to the increase of the radiation efficiency. At 3.2 kHz, extreme amplitude decrease and phase circulation are observed as seen on the vertical plane. This phenomena is observed in the narrow frequency range from 3.2 to 3.3 kHz (single phase circulation) and in higher frequencies above about 4.4 kHz (multiple phase circulation). And at frequencies a little higher than 3.3 kHz, the distribution of sound pressure is similar to that at 3.0 kHz.

A reason for the spatial circulation of phase at 3.2 kHz is considered to be the transverse resonance of the oral cavity. For the accurate evaluation of the resonance of the cavity, a 3-dimensional wave equation should be solved. However, we can consider a simple 2-dimensional model to explain the phase circulation. Let us assume that 2 parallel walls are located half of the wavelength apart. Then, a pure standing wave between the two walls, which implies transverse resonance, and forward and backward plane waves along the walls can exist. The acoustic field is the superposition of these waves. Fig.5 shows amplitude and phase contours computed by this model. The zero pressure point and phase circulation can be seen between the walls. The walls of the oral cavity have complicated shapes and it is not easy to find the representative size relating to the transverse resonance from their physical figuration. For the purpose of rough evaluation, if we compute this size inversely from the frequencies for the phase circulation by applying the above model, it becomes

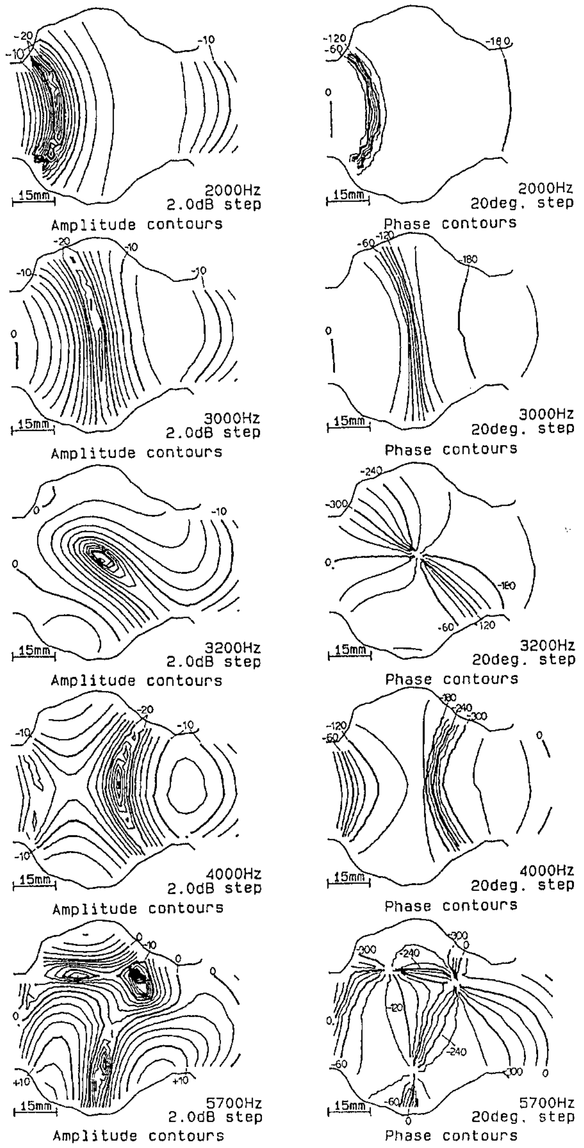

Fig.4 Amplitude and phase contours (horizontal plane of Replica(II)).

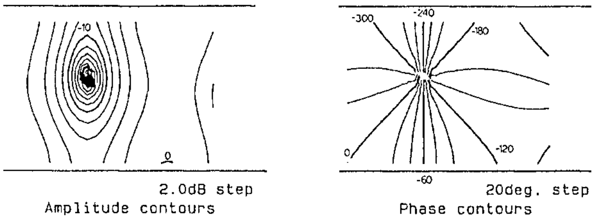

Fig.5 Amplitude and phase contours calculated from the model of plane waves in the field of an orthogonally directed standing wave. Sound pressure $p(x,y) = j\sin(2\pi y/\lambda) + e^{-j2\pi x/\lambda} + 0.8e^{j2\pi x/\lambda}$ $(|y| \leq \lambda/4)$, *where x and y are coordinates tangential and normal to the walls respectively and* λ *is the wavelength.*

about 54 mm, and is nearly the mean distance between the cheek walls. In the chart for 4.0 kHz in Fig.4, the amplitude near the spread cheek walls is relatively high (8.6 dB) and its distribution becomes saddle shaped. Above about 5.2 kHz, the distributions of amplitude and phase become asymmetric although the outlines of the walls are almost symmetric. The multiple phase circulation at higher frequencies may result from the interference of some waves traveling in different directions and forming a complex standing wave field.

3.2 Particle trajectory

The particle velocity is the other physical quantity characterizing the sound wave in the vocal tract and is related to the sound pressure by Euler's momentum equation. Using the measured distributions of sound pressure, we can obtain the particle velocity vectors or particle trajectories at each measuring position[6]. The calculated particle trajectories are shown in Fig.6. The outlines of the replica are the same as in Fig.3 and 4. The size of the major axis of each ellipse is proportional to the maximum displacement of the particle from its equilibrium position. At 3.0 kHz, trajectories are almost straight lines; vibration of each part of the medium is 1-dimensional. And it is clearly seen that particle trajectories become quite elliptical near the center of the phase rotation of sound pressure.

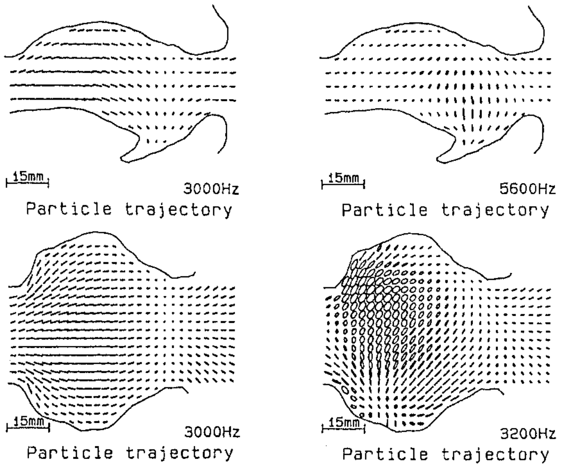

Fig.6 Particle trajectories.

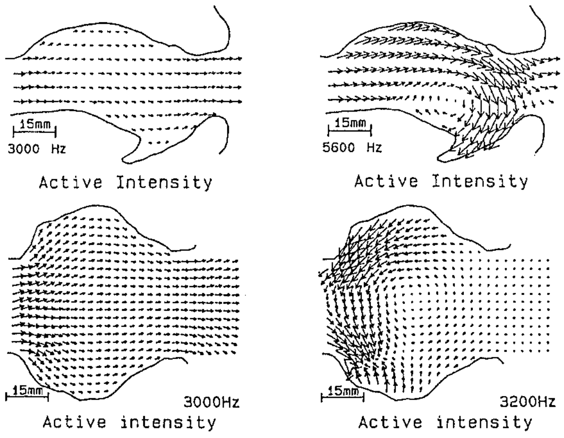

Fig.7 Vectorial maps of active intensity.

3.3 Sound intensity

Multiplying the measured sound pressure by the complex conjugate of the calculated particle velocity, we obtain complex acoustic intensity vectors which are closely related to the acoustic energy flow[7]. Vectorial maps of active intensity, which is the real part of the complex intensity vector, are shown in Fig.7. The length of each arrow is proportional to the linear magnitude of the intensity vector. A uniform intensity field is seen at 3.0 kHz. As the active intensity vectors are normal to the phase contours of sound pressure, active intensity vectors can form a vortex as seen in Fig.7. When the rotation of the vector field is zero, the route of acoustic energy flow can be estimated as any continuous line tangential to the active intensity vector at each point. However, if the rotation is not zero, the route cannot be obtained from only the active intensity vectors. Instantaneous intensity representation is required[8].

4. CONCLUSIONS

The characteristics of the distribution of sound waves in the oral cavity were discussed based on acoustic measurement. The amplitude of sound pressure tends to be relatively high at the anterior bottom of the oral cavity while the phase contours are aligned in an almost anterior-posterior direction up to about 4 kHz except at particular frequencies at which a phase circulation around a zero pressure point occurs. A simple 2-dimensional model can well simulate the phenomenon of this phase circulation. The amplitude and phase distributions of sound pressure can describe the acoustic field completely, and other physical quantities can be calculated from these distributions. Detailed measurement for various articulatory shapes should be performed to produce a model for wave propagation in the vocal tract.

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