SOME PROPERTIES OF AN AEROACOUSTICS CHARACTERIZATION OF PHONATION

Richard S. McGowan
Haskins Laboratories
270 Crown Street
New Haven, CT 06511, U. S. A.

ABSTRACT

When the conservation equations governing the motion of air are considered, it is seen that there are sources of sound during phonation other than the volume velocity at the glottis. One possible source is the result of forcing between the solid surfaces near the glottis and the air. Approximations based on a schematic vocal tract show this source to be relatively weak compared with the volume velocity source.

Sources of sound during phonation will be discussed in this paper. The plural is used because there are other acoustic sources than the volume velocity source during phonation. These other sources appear when the three-dimensional character of the fluid velocity field in the vocal tract is considered, showing that a one- dimensional characterization is not enough when considering vocal tract sound production. While one-dimensional models using volume velocity and pressure for dependent variables may be good approximations when considering plane wave propagation of sound, such models do not correctly characterize the production of sound during phonation. These one-dimensional models, or analogs, are based on what is known as a scalar field theory because the dependent variables are scalar.

Both the sound production and sound propagation parts of the one-dimensional analogs should be derivable from the equations of motion for air. The equations of motion of air provide what is known as a vector field theory, because the vector, fluid particle velocity is used instead of the scalar, volume velocity. Here, the inadequacy of the one-dimensional scalar description of the sound source will be discussed by going back to the more primitive notions of the fluid mechanics of air: mass, momentum, and energy conservation. From this point of view, it will be seen that volume velocity supplies only part of the picture in sound production.

Theoretical aeroacoustics is a branch of fluid mechanics providing a means of describing the sources of sound from the conservation equations. The literature in this field is extensive (e.g.[1]) and some of it will be used here. Initially, we will concentrate on the basic differences between the aeroacoustic view and that provided by the current analogs. The real vocal tract will be schematized to illustrate some of the basic principles of the aeroacoustic view. As a result, the sources of sound named here may have to be modified when applied to a real vocal tract.

Because of the extra degrees of freedom provided by the vector nature of fluid mechanics, we can decompose the fluid velocity field, $\underline{u}$, into two separate vector fields, the solenoidal field and the irrotational field [2].

$$\underline{u} = \underline{u}_S + \underline{u}_I \tag{1}$$

The solenoidal field, $\underline{u}_S$, will support rotational motion but not compression and expansion, while the irrotational field, $\underline{u}_I$, can support compression and expansion, but not rotation. Because acoustic motion needs the potential energy of compression and expansion, the irrotational field is a necessary part of such motion. However, the solenoidal field can provide sources of sound, since solenoidal, incompressible fluid motion can provide pressure fluctuations. This field is ignored by the one-dimensional analogs, where all the motion is irrotational, and therefore the one-dimensional analogs ignore possible acoustic sources. Even after the decomposition of the fluid velocity field given by equation (1) has been performed, the three- dimensional character of the solenoidal field also needs to be considered. The full three-dimensional character of the solenoidal field itself needs to be considered because

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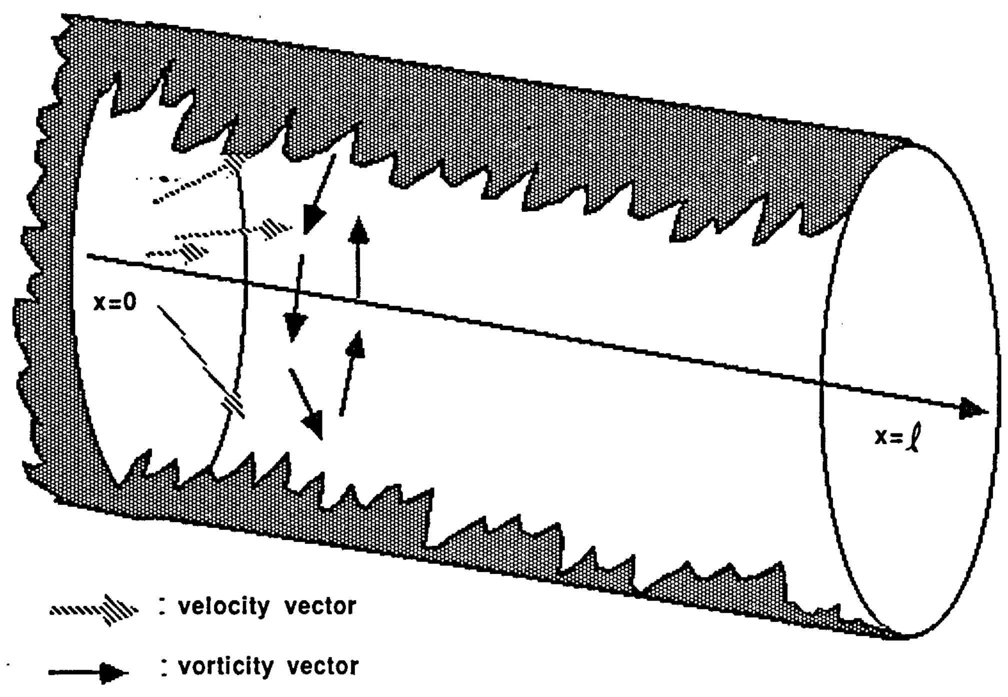

Figure 1: schematic vocal tract

it will be seen that interaction between vectors, derived from this field, provides one example of a sound source. This sound source involves rotational motion of the air.

The sound source involving rotational motion of the air can be derived by considering a particular geometric feature of the vocal tract near the glottis. This feature is the abrupt area change from the glottis into the vocal tract. We will consider the vocal tract to be a straight, semi-infinite, cylindrical tube with an abrupt area change representing the glottis at x = 0 and a mouth at x = l (see Figure 1). The source of sound occurring in such a geometrical configuration will be considered with the understanding that the source could be altered when more features of the geometry of the real vocal tract are considered. To provide a detailed account of sound production would be premature and beyond the scope of this paper. It is well known that there is rotational motion which results when there is flow through a sudden change in area. Rotational motion of the fluid can be inferred from a large drop in pressure head, or stagnation pressure, p_{st}:

$$p_{st} = p + \frac{\rho_0}{2}|\underline{u}|^2 \qquad (2).$$

where p = static pressure and ρ_0 = rest density of air. Pressure head losses have been observed in experiments using static configurations (e.g.[3]). Although investigators have attributed a large portion of the pressure head loss they observed to the formation of turbulence, which is both random and rotational motion of the fluid, it is the rotational motion of the fluid which is the essential factor. In the current analog models this pressure head loss is modeled as a nonlinear resistor without acoustic consequences, other than determining the relationship between transglottal pressure and the volume velocity. Using the theory of aeroacoustics, this head loss is seen as a singularity having consequences in the acoustic far-field.

Note that pressure head loss is known to occur on both sides of model glottis', but the loss above the glottis will have the greatest acoustic consequences in the supraglottal region, so this will be examined more closely. Also, the experiments have been on static configurations, where the results are applied to dynamic phonation with the quasi-steady approximation. (In the dynamic situation it is less likely that the rotational fluid motion just above the glottis is also random.) While the quasi-steady approximation allows for easy estimation of pressure head loss [4], it is not a necessary approximation for asserting the existence of such a head loss in a dynamic situation. It has been shown experimentally that the head loss also occurs in the dynamic situation [5].

Before the acoustic consequences of the head loss are discussed, the cause of the loss from the point of view of the equations of motion need to be discussed. The cause has to do with the formation of vorticity. Vorticity, $\underline{\omega}$, is a function of the velocity vector itself, and provides a measure of the rotational motion of the fluid.

$$\underline{\omega} = \nabla \times \underline{u} \qquad (3)$$

We can imagine an oscillating jet of air exiting from the glottis, and, eventually, expanding into the cylinder. By the definition of the curl and the symmetry of the configuration, the vorticity can be expected to be directed azimuthally about the axis of the cylinder. (There is assumed to be no azimuthal component of velocity, and there is no dependence of the other components on the azimuthal angle.) In fact, the secondary flow just above the glottis may be in the form of a vortex ring.

As evidenced by the loss of pressure head above the glottis, there is a forcing between the solid surfaces and the air. This force is realized in the fluid as what can be called the vorticity-velocity interaction force (per unit volume):

$$\rho_0(\underline{\omega} \times \underline{u}).$$

The radial components for these vectors tend to cancel one another, while the axial components are directed away from the glottis. The net result (in a spatial average) is a vector directed away from the glottis in the axial direction. Because the velocity has a time averaged component, as well as a fundamental and harmonics, the vorticity-velocity interaction force will contain the same frequencies in its spectrum as the velocity, although with different weights. That the loss of pressure head is the result of this forcing can be derived from the momentum conservation equation for an inviscid fluid, Euler's equation, under the quasi-steady approximation [6]. The negative of the gradient of the pressure head is equal to the vorticity-velocity interaction vector:

$$\nabla p_{st} = -\rho_0(\underline{\omega} \times \underline{u}) \qquad (4).$$

From the above discussion, this gradient is directed against the axial direction, which is consistent with what is observed in the static experiments. In the following, the acoustic consequences of such a force will be considered as some basics of sound production are discussed.

To create sound, we can make local density fluctuations by changing the volume of fluid in a region small compared with the wavelength of sound in an oscillatory way. Such a source is called a monopole source, an example of which is provided by the volume velocity entering the vocal tract. If two monopole sources, 180 degrees out of phase, are put near one another (on the scale of wavelength), a dipole source is created. Such a source is inefficient because there is a great amount of partial cancellation [7]. An oscillating force within air causes air to accelerate from one region to another without an overall change in density, and so, resembles the dipole source just mentioned, if the force is active in a region small compared with wavelength. If it is assumed that the pressure head loss above the glottis occurs in a region short compared with wavelength, then the vorticity-velocity interaction force can be said to provide a dipole source of sound (see equation (4)). (In the static experiments the loss appears to occur within 2 cm. of the glottis, which means that this should be a good approximation up to about 3000 Hz.)

What effect does this dipole source have on the sound in the schematic vocal tract ? We follow the aeroacoustic theory of Powell [8], which was later elaborated by Howe [9], to draw the following picture. The oscillating volume velocity at the glottis can be considered a monopole source of irrotational fluid motion, which would be heard as sound in the far-field if nothing else was to intercede. However, because of the abrupt area change, there is a transfer of energy from the irrotational fluid motion to rotational motion. The forcing associated with the transfer of energy is the vorticity-velocity interaction force. Further, this force provides a dipole source of sound. The one-dimensional analogs, while providing a resistance to the volume flow, do not account for the radiation of the pressure fluctuations of the rotational fluid motion. The picture presented here is similar to that described by Howe [10] and Bechert [11] for the attenuation of low frequency sound transmitted from a low Mach number jet.

It is of interest to estimate the ratio of the strengths of the acoustic fields due to these sources. Without filling in the mathematical details, the relative strengths of the two sources can be considered, as well as the efficiency with which they radiate. Suppose the glottal fluid particle velocity is a rectangular wave and the glottal area is a triangular wave. Further, suppose the ratio of the vocal tract area to the glottal area is greater than or equal to five, the duty cycle is greater than one-third, and that the quasi-steady approximation holds. It can be shown that the ratio of the dipole source strength to the monopole source strength goes as the first power of the glottal Mach number, the first power of the ratio of the vocal tract area to the maximum glottal area, and to the first power of the frequency to a good approximation above, say, the second harmonic. As may be expected from the fact that the dipole source strength is a nonlinear function of fluid particle velocity, the importance of this source grows with frequency, after a given frequency.

As far as the efficiency of radiation, the monopole, volume velocity source appears to be efficient because it is located at a high impedance boundary: the glottis. The result is a velocity source at a pressure maximum, which means efficient energy exchange. On the other hand, the dipole source is a pressure type source, located just above the same boundary. This will mean an inefficient radiation, which will improve with frequency, at least as long as the source region is short compared with wavelength (recall the discussion on dipoles). In this frequency regime, the ratio of the the acoustic field due to the dipole source to that due to the monopole source increases as the first power of the frequency.

In the estimates made above, the impedance looking into the glottis is presumed infinite. This allows us to prescribe the input volume velocity into the vocal tract, and it allows us to say that the efficiency of radiation of the volume velocity source is a constant function of frequency. To account for source-tract interaction, a finite, time varying impedance at the glottis needs to be considered. This impedance may be difficult to deduce. The subglottal region needs to be considered as part of the acoustic system and the appropriate Green's, or transfer, function derived for this more complicated geometry. While the imposition of an explicit boundary condition at the glottis is avoided in this manner, other difficulties arise, such as the the fact that different ambient conditions apply in the subglottal and supraglottal regions.

CONCLUSION

Using the three-dimensional character of the fluid velocity field and the geometric property of sudden change in area, a sound source, other than volume velocity, can be identified. This source is a dipole type source, and is a poor radiator at low frequencies. Other modifications to the picture of sound sources during phonation can be expected when a more realistic geometry is considered (e.g. the epiglottis). The difficult question of source-tract interaction needs to be considered by looking at both the subglottal and supraglottal regions simultaneously. A more satisfactory picture of the acoustics of phonation can result by deriving the acoustic field from the conservation equations governing the motion of air.

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