880

The quasisteady approximation in speech production

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Because boundary-layer separation is important in determining force between flowing air and solid bodies and separation can be sensitive to unsteadiness, the quasisteady approximation needs to be examined for the flow-induced oscillations of speech (e.g., phonation and trills). A review of the literature shows that vibratory phenomena, such as phonation and tongue-tip trills, may need to be modeled without the quasisteady approximation.

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The quasisteady approximation is commonly made in modeling air flow and vibration in speech production. Experimentally, the quasisteady approximation means that time-varying situations, such as vocal fold oscillation or tongue-tip trills, can be studied with a series of static configurations simulating the air flow in a vocal tract. For mathematical modeling purposes, the quasisteady approximation means that acceleration terms involving partial derivatives with respect to time in the equations of motion of air can be neglected. This allows the modeling of air flow as a sequence of static flow configurations. Although an inductive term representing the effect of acceleration of air in the constriction is often included in mathematical modeling, other unsteady effects are ignored. When the quasisteady approximation is made, vorticity and turbulence distributions, important in force and energy balance considerations, are assumed to be unaffected by unsteady air acceleration. In particular, the quasisteady approximation is applied to boundary-layer separation, which is an important determinant of vorticity distribution, and, hence, of the energy exchange between the air and solid in flow-induced oscillations, such as phonation and tongue-tip trills. However, a review of recent literature (e.g., Bertram and Pedley, 1983; Sobey, 1983; Cancelli and Pedley, 1985; Pedley and Stephanoff, 1985; Sobey, 1985) shows that the quasisteady approximation can only be used with great care in the fluid mechanics regimes involving boundary-layer separation. Because boundary-layer separation occurs in the vocal tract, these recent works bear consideration for understanding speech production. Some of the recent literature that brings the quasisteady approximation into question will be reviewed here, after some of its relevance to speech production modeling has been discussed.

The fact that characteristic Strouhal numbers are often small in speech has been used to justify the quasisteady approximation. For periodic motion the Strouhal number is the product of a characteristic frequency and characteristic length scale divided by a characteristic velocity, and it is the coefficient of the time derivative terms in nondimensional versions of the mass and momentum conservation equations. If the Strouhal number is small compared to one, it is presumed that these terms can be neglected, that is, it is possible to make the quasisteady approximation. (This assumes that other terms are of order one, which is generally the case.) The quasisteady approximation is often used in aerodynamic considerations for the modeling of phonation, stop release, and fricatives. For phonation, with maximum air speeds in excess of 2000 cm/s, frequencies on the order of 100 Hz, and length scales at most on the order of 1 cm, producing a Strouhal number less than 0.05, this may appear to be a valid approximation to use for simplifying a model (Catford, 1977, p. 98). Before reviewing the reasons that this may be faulty, it is necessary to consider boundary-layer separation and its importance for vibratory phenomena in the vocal tract.

When air flows over a solid surface, a layer of air with a high concentration of vorticity is formed next to the solid surface, and this layer is a boundary layer. Boundary-layer separation occurs at places on the surface of a solid where the vorticity of the boundary layer abruptly leaves the region close to the solid boundary and is subsequently convected by the flow. The places where separation occurs are called separation points. (A separation point in two-dimensional modeling represents a line of separation in the third dimension.) Separation occurs where there is a sufficient adverse pressure gradient, as occurs when flow is decelerated (Lighthill, 1963). An adverse pressure gradient occurs when there is flow along solids from regions of low pressure to regions of high pressure and if the spatial rate of change of pressure is sufficiently large, the boundary layer will separate. For example, the flow from the constriction for an /s/ separates because of the abrupt, adverse pressure change caused by the sudden area expansion after the constriction. During phonation, the flow separates from the folds, thus providing the time-varying flow resistances that are essential for the production of modal voice (Ishizaka and Flanagan, 1972).

The locations of separation points are important for the study of flow induced oscillations in the vocal tract because they help to determine the forces between the air and the tissue. Because vorticity is transported from the boundary layer into the main portion of the flow field at a separation point, there can be a change in pressure head in traversing the region near a separation point. A net force on a blunt object in the direction of flow can result from such a pressure head difference. There is likely to be a separation point near the boundary between the windward and the leeward sides of such an object because of the

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adverse pressure gradient. (There is an adverse pressure gradient because the flow slows down on the leeward side.) The windward side has a higher pressure head than the leewad side, so there is a higher static pressure on the windward side than on the leeward side. These considerations are important for the energy exchange between moving objects and the air, because energy is the integral of force against distance moved. Thus, the change in boundary-layer separation behavior with the removal of the quasisteady approximation may have important consequences in modeling flow induced oscillations of speech, such as phonation and tongue-tip trills.

In the last decade the quasisteady approximation for internal flows (e.g., flows inside the vocal tract), even at a very small Strouhal number, has been questioned. The Reynolds number, equal to the product of a characteristic velocity and length scale divided by the kinematic viscosity, has been shown to be an important parameter for questions of unsteadiness. Pedley (1983), in a review article on physiological fluid flows, quotes results on channel flows driven sinusoidally from a side wall with amplitudes of between 0.28 and 0.57 of the channel width. For Reynolds numbers of between 300 and 700 based on cross sectionally averaged, steady fluid particle velocity and channel width, quasisteady behavior disappears for a Strouhal number of about 0.008. A vortex wave is observed to travel downstream from the oscillating portion of the wall (Pedley and Stephanoff, 1985; Sobey, 1985), which is not predicted by quasisteady theory. There is also other behavior that marks the inadequacy of the quasisteady approximation in unsteady flow. Bertram and Pedley (1983) have shown experimentally that impulsively started flow over an indentation of the channel wall can create separated flow on the lee side of the indentation, with the separation point moving upstream as the steady state is approached. Sobey (1983) has used numerical simulations of unsteady flow in channels with wavy walls to show the moving separation point on the lee slopes of the wavy walls. For a Reynolds number based on peak velocity and minimum channel half-width of only 75 and a Strouhal number of 0.01, there are qualitative differences in the separation behavior from that expected from the quasisteady approximation. For one thing the flow, once separated during acceleration, does not reattach to the walls after deceleration to zero flow. Requiring that separation vorticity disappears when the flow reverses in oscillatory flow, Sobey derived a very restrictive relation between Strouhal number and Reynolds number for the quasisteady approximation to be valid. The Strouhal number must be less than 0.2 of the square inverse of the Reynolds number. For a Reynolds number of 100 the Strouhal number would need to be less than 0.00002 to meet Sobey's criterion for quasisteady behavior. Thus, a small Strouhal number is not sufficient to ensure quasisteady behavior.

Sobey (1983) furthermore gives an argument as to why unsteady separation phenomena are different from steady separation phenomena, even at very small Strouhal numbers. In unsteady flow, the fluid particle velocity at a point in space can be considered both a function of time and a function of a time-variable Reynolds number. To obtain the total time derivative of the fluid particle velocity, one needs to include a term that is the derivative of the fluid particle velocity with respect to Reynolds number times the time derivative of the Reynolds number. Because flow conditions are singular near a separation point, the derivative of flow velocity with respect to the Reynolds number in a region of a separation point can be quite large. Thus, the total time derivative does not scale exclusively with Strouhal number near a separation point, but also depends on the Reynolds number.

It is easily seen, using Sobey's criterion, that flow-induced oscillations in speech may not be quasisteady if flow separation is concerned. Based on maximum velocity of 2000 cm/s and characteristic dimension of 1 cm, the Reynolds number during phonation is about 13 000. The Strouhal number for phonation is 0.05 based on a 100-Hz oscillation frequency. Based on an oscillation frequency of 30 Hz, the tongue-tip trill Strouhal number is 1/3 of that for phonation, and the Reynolds number is in the same range as that for phonation (McGowan, 1992). Thus, both these vibratory phenomena should be considered to be truly unsteady and the quasisteady assumption seriously questioned.

One possible consequence of unsteadiness may be a mechanism for energy exchange from air to solid during vibration. For instance, for essentially one-degree-of-freedom solid motion during falsetto voice there could be a hysteresis in the separation point position between opening and closing phases of the motion. If the separation point tends to be further forward during the opening phase than during the closing phase, the pressure on the upstream portion of the folds could be greater during the opening than during the closing phase. This mechanism could supplement others, including glottal air induction that depends on vocal fold position (Wegel, 1930) and an inductive loading of the supraglottal vocal tract (Flanagan and Landgraf, 1968; Ishizaka and Flanagan, 1972) in accounting for energy exchange.

In this letter, it has been shown that the quasisteady approximation may not be a valid approximation in speech, particularly when flow separation is involved. Unsteady effects may have to be included to account for some aspects of phonation and tongue-tip trills. For instance, mechanisms proposed for the energy exchange from air to the vocal folds when each vocal fold has essentially one degree of freedom may be supplemented with a moving separation point.

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