Dynamic line analogs for speech synthesis

Liljencrants, J.

journal: STL-QPSR
volume: 26
number: 1
year: 1985
pages: 001-014

http://www.speech.kth.se/qpsr
I. SPEECH PRODUCTION

A. DYNAMIC LINE ANALOGS FOR SPEECH SYNTHESIS *

Johan Lijencrantz

Abstract

The Kelly-Lochbaum line analog and recent developments by Maeda (1978) and Strube (1982) to include effects from dynamic area variation are outlined. The Maeda model preserves continuity in pressure and flow while the Strube model is based on continuity in pressure and longitudinal momentum. A simple heuristic correction procedure that gives similar results is presented. All the methods are shown as differential corrections to the original static model.

The different models are compared in three dynamic tests. It is found that the Strube model is closer to physical reality in accounting for dynamic effects on bandwidth. If the area data is under-sampled, which is desirable in practical applications, then the Maeda model is less prone to generate spurious artifacts.

THE KELLY-LOCHBAUM LINE ANALOG AND EXTENSIONS

The reflection type line analog described by Kelly and Lochbaum (1962), the K-L model, to simulate wave propagation in the vocal tract is set up as a sequence of N uniform tubes of equal length l = c/2t. \( t \) is the sample interval, and the tubes have different areas \( A_n \). It stems from the general solution to the wave equation that says that the pressures and flows along the line can be put in terms of a forward and a backward going partial wave system.

Let the partial pressure waves be \( p \) for the forward and \( q \) for the backward. The total resulting pressure and flow in a tube is then

\[
P = p + q \\
U = (p - q) \times A/c
\]

where \( A/c \) is the acoustic impedance of the tube having area \( A \) and \( c \) is the wave impedance of air.

Attach to them a numeric subscript for the tube number and an alphabetic for time sample number. Within each tube a partial wave propagates undisturbed, but when it reaches a joint it is split into two parts. One part goes on in the same direction into the next tube and the other part is reflected back into the old tube in the opposite direction, Fig 1.

![Diagram showing tube joint with wave scattering](image)

Fig. 1. Tube joint with wave scattering. To the left physical arrangement, to the right space-time diagram of partial waves.

The basic problem is to find the "scattering equations", that is, to find the resultant $p_{2b}$ and $q_{1b}$ expressed in the incident $p_{1a}$, $q_{2a}$, and the areas or impedances involved. The classical solution is found from the assumption of continuity in total pressure $P$ and flow $U$ at the joint, these being

$$P = p_{1a} + q_{1b} = p_{2b} + q_{2a}$$

(2)

$$U = (p_{1a} - q_{1b})A_1/\rho c = (p_{2a} - q_{2b})A_2/\rho c$$

and the solution to this by eliminating $P$ and $U$ may be put as the "one multiplier lattice"

$$P_{2b} = p_{1a} + t_{12} ; \quad t_{12} = k_{12}(p_{1a} - q_{2a})$$

(3)

$$q_{1b} = q_{2a} + t_{12}$$

Here a reflection coefficient is defined, equivalently in terms of areas or impedances, as

$$k_{12} = \frac{A_1 - A_2}{A_1 + A_2} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

(4)

FLOW, VELOCITY, AND FORCE PARTIAL WAVES

It is not always recognized that one can make an exactly analogous derivation, but instead of the pressure waves $p$ and $q$, using flow waves, let us call them $r$ forward and $s$ backward. The solution will then be the flow scattering equations

$$r_{2b} = r_{1a} - u_{12} ; \quad u_{12} = k_{12}(r_{1a} + s_{2a})$$

(5)

$$s_{1b} = s_{2a} + u_{12}$$

$k_{12}$ as in (4) is identical with the one for the pressure wave analogy. Whether to use the pressure waves $p$, $q$ or the flow waves $r$, $s$ for simulation purposes is much an arbitrary choice. The only obvious difference in the scattering equations for the two cases is that of a few signs.

It may also be interesting to note that one could use partial waves pertaining to a mechanical analog rather than an acoustic. These waves are then velocity waves or force waves. The choice between pressure or velocity analogy is then immaterial, as is the choice between flow or force, except for the scaling constant $\rho c$. But conversely the choice
between pressure or flow does have a significance for the operation of the model, and these two cases will be treated in parallel in the following.

One difference between the pressure and flow wave analogies that has an interest in hardware implementations is in the numerical magnitude of the partial waves. With the flow analogy the partial waves always have moderate numerical values, but with the pressure analogy there is a risk of numerical overflow at the combination of a significant net flow with a very small area. In fact, a point of major interest is how the models behave when the area of a section is taken down to zero (or usually, to avoid numerical trouble, a very small value) in order to simulate a closure. To obtain such a cutoff it is inevitable that the relative change in area from one sample interval to the next is very substantial. This can generate artifacts in the signals unless the model is dynamic, that is, in itself accounts for area change with time.

DYNAMIC LINE MODELS

The problem of developing a dynamic line analog has been addressed by Ruiz (1971), Maeda (1977), and Strube (1982). First the published Maeda and Strube models will be outlined, using the present notation, as in Fig 1. The dynamic aspect enters the following way. Simultaneously with the waves reaching the joint then also the impedances (areas) of the tubes change. Thus we have four impedances involved, one for each quadrant in the time-space diagram.

The continuity argument of Maeda is that there is some pressure $P$ and flow $U$, both continuous at the crossover point. Augmenting with areas $A_{1a}$, $A_{1b}$, $A_{2a}$, and $A_{2b}$, eliminating $P$ and $U$, and solving for the resulting waves the scattering equations will be

$$p_{2b} = p_{1a} + k_p*(p_{1a} - q_{2a})$$

$$q_{1b} = q_{2a} + k_q*(p_{1a} - q_{2a})$$

arranged here similarly to Eq. (3). To get this analogy of form we must use two different reflection coefficients $k_p$ and $k_q$, one for each wave direction. Introducing the changes of impedance $\Delta Z_2 = Z_{2b} - Z_{1a}$ and $\Delta Z_1 = Z_{2a} - Z_{1a}$ will bring out the difference in Maeda's model compared to the static case as

$$k_p = \frac{Z_{2b} - Z_{1a}}{Z_{2a} + Z_{1a}} = k_{12a} + \frac{\Delta Z_2}{Z_{1a} + Z_{2a}}$$

$$k_q = \frac{Z_{2a} - Z_{1b}}{Z_{2a} + Z_{1a}} = k_{12a} - \frac{\Delta Z_1}{Z_{1a} + Z_{2a}}$$
where \( k_{12a} \) is identical to the static reflection coefficient \( k_{12} \) of Eq. (4) using the impedances \( Z_{1a} \) and \( Z_{2a} \) in effect before the impedance change.

Strube (1980) questions this result and argues on physical grounds that the time average of pressure waves \( p, q \) is continuous in space, and that the space average of longitudinal momentum \( p/\bar{z}, q/\bar{z} \) is continuous in time. This eventually again leads to scattering equations with two different reflection coefficients

\[
p_{2b} = p_{1a} + k_1^* p_{1a} + k_2^* q_{2a}
\]

\[
q_{1b} = q_{2a} + k_1^* p_{1a} + k_2^* q_{2a}
\]

but now with

\[
k_1 = \frac{A_{1a} - A_{2b}}{A_{1b}^2 + A_{2b}^2} = k_{12b} - \frac{\Delta A_1}{A_{1b}^2 + A_{2b}^2}
\]

\[
k_2 = \frac{A_{1b} - A_{2a}}{A_{1b}^2 + A_{2b}^2} = k_{12b} - \frac{\Delta A_2}{A_{1b}^2 + A_{2b}^2}
\]

\( k_{12b} \) is still the static reflection coefficient, but this time using the areas after the area change.

CORRECTION APPROACH TO DYNAMIC MODELLING

In practice one would like to supply new data on areas or reflection coefficients at a lower rate than the sampling frequency. Each time new area data is supplied in presence of signals there will, however, come up some transients in the partial waves. The following method was developed as a means to get rid of these transients.

Then, instead of considering the tube joints at the time of reflections, let us focus on a specific tube. Here the net pressure and flow can be inferred from Eq. (1), even if this is strictly valid only just at the time of reflections. Let us suddenly change the area or impedance of that tube. The continuity requirement posed is that the pressure and flow remain unchanged in the tube. Since we are concerned with a single tube the space subscript is now omitted. Applying Eq. (1) with this constraint and the pressure analogy leads to

\[
p_b = p_a - (p_a - q_a)^* \Delta A/2A_b
\]

\[
q_b = q_a + (p_a - q_a)^* \Delta A/2A_b
\]
The procedure is then: whenever the area of a tube in the line analog is changed, then with Eq. (10) compute a new pair of forward and backward waves, for that tube only, from the existing waves and the area change. Also, before the scattering equations are executed of course the reflection coefficients at the ends of that tube have to be recomputed. For the scattering computations the static Eqs. (3) or (5) are used.

Let me call this procedure: adjustment for P-U continuity.

With this wave adjustment procedure the dynamic model is split up into two separate parts, one to take care of the area change, and one to take care of the scattering. With both partial procedures the underlying requisite was that total pressure P and net flow U were continuous in time and space. A close correspondent to this should be the dynamic scattering of Maeda that was derived from the same basic criteria. Tests have shown that the Maeda model and the P-U adjustment do indeed give very similar results.

Another invention is to try a different wave adjustment, this time with a continuity requirement similar to the one posed by Strube, that of continuity in P*A and U/A. (Not exactly like: we do not dispose of the space dimension inside a single tube). This comes out slightly different as

\[ p_b = p_a - (p_a + q_a) \frac{\Delta A}{2A_b} \]
\[ q_b = q_a - (p_a + q_a) \frac{\Delta A}{2A_b} \]  \hfill (11)

Let me for simplicity call this: adjustment for f-v continuity (force and velocity, in regard of the dimensions of P*A and U/A).

Table 1 contains a comprehensive list of alternatives for the scattering equations, static and dynamic. They are written in a form to make mutual comparisons easy, which to some extent implies that the form is not optimal for computer programming without further rearrangement. As a parallel set the table also lists the corresponding equations for the flow wave analogy.

**Tests of the Scattering Equations**

We have now ten candidates for the scattering problem: pressure and flow analogy, and for each of those the static solution, two dynamic, and two approximately corresponding wave adjustment proposals. Needless to say they all give identical results with a line that is time invariant. But with a time varying line the models do behave differently. I have tried the models in a number of different tests and will now describe three of those that give quite different results.
Table 1. Summary of static and dynamic scattering equations for pressure waves p, q, and flow waves r, s. The equation pairs are written without abbreviations in a form to clearly show mutual differences between cases.

1, 2, n are consecutive subscripts in space, a, b in time.

**STATIC REFLECTION COEFFICIENT**

\[
k_{12} = \frac{A_1 - A_2}{A_1 + A_2} = \frac{Z_2 - Z_1}{Z_1 + Z_2} \quad Z_n = \frac{\rho c}{A_n}
\]

**CHANGE WITH TIME IN AREA AND IMPEDANCE**

\[
\Delta A_n = A_{nb} - A_{na} \quad \Delta Z_n = Z_{nb} - Z_{na} \quad n = 1, 2
\]

**STATIC SCATTERING**

**PRESS**

\[
\begin{align*}
p_{2b} &= p_{1a} + (p_{1a} - q_{2a}) \cdot k_{12} \\
q_{1b} &= q_{2a} + (p_{1a} - q_{2a}) \cdot k_{12}
\end{align*}
\]

**FLOW**

\[
\begin{align*}
r_{2b} &= r_{1a} - (r_{1a} + s_{2a}) \cdot k_{12} \\
s_{1b} &= s_{2a} + (r_{1a} + s_{2a}) \cdot k_{12}
\end{align*}
\]

**DYNAMIC: Continuity in P and U**

**DYNAMIC SCATTERING (Maeda), time index a: early k, Z and A**

**PRESS**

\[
\begin{align*}
p_{2b} &= p_{1a} + (p_{1a} - q_{2a}) \cdot k_{12a} + \frac{(p_{1a} - q_{2a}) \cdot \Delta Z_2 / (Z_{1a} + Z_{2a})}{(\Delta A_1 + \Delta A_2) / (A_{1a} + A_{2a})} \\
q_{1b} &= q_{2a} + (p_{1a} - q_{2a}) \cdot k_{12a} - \frac{(p_{1a} - q_{2a}) \cdot \Delta Z_1 / (Z_{1a} + Z_{2a})}{(\Delta A_1 + \Delta A_2) / (A_{1a} + A_{2a})}
\end{align*}
\]

**FLOW**

\[
\begin{align*}
r_{2b} &= r_{1a} - (r_{1a} + s_{2a}) \cdot k_{12a} + \frac{(r_{1a} + s_{2a}) \cdot \Delta A_2 / (A_{1a} + A_{2a})}{(\Delta A_1 + \Delta A_2) / (A_{1a} + A_{2a})} \\
s_{1b} &= s_{2a} + (r_{1a} + s_{2a}) \cdot k_{12a} + \frac{(r_{1a} + s_{2a}) \cdot \Delta A_1 / (A_{1a} + A_{2a})}{(\Delta A_1 + \Delta A_2) / (A_{1a} + A_{2a})}
\end{align*}
\]

**SINGLE TUBE WAVE DYNAMIC CORRECTION**

**PRESS**

\[
\begin{align*}
p_{b} &= p_{a} - (p_{a} - q_{a}) \cdot \Delta A / 2A_b \\
q_{b} &= q_{a} + (p_{a} - q_{a}) \cdot \Delta A / 2A_b
\end{align*}
\]

**FLOW**

\[
\begin{align*}
r_{b} &= r_{a} - (r_{a} + s_{a}) \cdot \Delta Z / 2Z_b \\
s_{b} &= s_{a} - (r_{a} + s_{a}) \cdot \Delta Z / 2Z_b
\end{align*}
\]

**DYNAMIC: Continuity in PA and U/A, P/Z and UZ, or force and velocity**

**DYNAMIC SCATTERING (Strube), time index b: late k, A and Z**

**PRESS**

\[
\begin{align*}
p_{2b} &= p_{1a} + (p_{1a} - q_{2a}) \cdot k_{12b} - \frac{(\Delta A_1 + \Delta A_2) \cdot q_{2a}}{(A_{1b} + A_{2b})} \\
q_{1b} &= q_{2a} + (p_{1a} - q_{2a}) \cdot k_{12b} - \frac{(\Delta A_1 + \Delta A_2) \cdot p_{1a}}{(A_{1b} + A_{2b})}
\end{align*}
\]

**FLOW**

\[
\begin{align*}
r_{2b} &= r_{1a} - (r_{1a} + s_{2a}) \cdot k_{12b} - \frac{(\Delta Z_1 + \Delta Z_2) \cdot s_{2a}}{(Z_{1b} + Z_{2b})} \\
s_{1b} &= s_{2a} + (r_{1a} + s_{2a}) \cdot k_{12b} + \frac{(\Delta Z_1 + \Delta Z_2) \cdot r_{1a}}{(Z_{1b} + Z_{2b})}
\end{align*}
\]

**SINGLE TUBE WAVE DYNAMIC CORRECTION**

**PRESS**

\[
\begin{align*}
p_{b} &= p_{a} - (p_{a} + q_{a}) \cdot \Delta A / 2A_b \\
q_{b} &= q_{a} - (p_{a} + q_{a}) \cdot \Delta A / 2A_b
\end{align*}
\]

**FLOW**

\[
\begin{align*}
r_{b} &= r_{a} - (r_{a} - s_{a}) \cdot \Delta Z / 2Z_b \\
s_{b} &= s_{a} + (r_{a} - s_{a}) \cdot \Delta Z / 2Z_b
\end{align*}
\]
Shutter test

The first is the 'shutter test' where a single tube section is stepwise varied and the signal is pseudo DC. The purpose is to show what happens when area is changed in large relative steps, as happens close to an area cutoff. A line made of three tubes as in Fig. 2a is simulated. The end tubes constantly have unit area and are externally excited. A constant forward wave is injected into tube 1 and a slowly varying ramp for the backward wave enters tube 3. The particular design of these inputs makes the test cover the range from zero static pressure and unit net flow up to zero flow and unit pressure. The waves leaving the end tubes are neglected, the simulation thus covers a reflection-free termination at both ends of the three tube array.

A result is shown as functions of time in Fig. 3. The upper trace of the figure shows the area of the middle 'shutter' tube. Initially a remark to what is not shown. For each model the resulting pressures and flows come out the same, either the pressure or the flow analogy is used, though the partial waves do not.

For the static model, when the area of the middle tube is suddenly made smaller, we see transients in the line. These transients gradually die out as the waves adapt to the new situation of areas and reflection coefficients. The time constant in the decay of the transients is actually inversely proportional to the area of tube 2. If this area is very small, it will take a long time before the waves trapped inside it manage to get out through the barriers of near total reflection at its ends. Similar transients come in the adjacent tubes (not shown). When the middle area is switched back to unit size, another transient is generated in the neighbor tubes. This one lasts only one time slot, after that it disappears without reflections out through the ends of the tube array.

A specific observation in this test is that after the transients are gone, then the pressure and flow in the shutter are the same as in its neighbors, and also the same as they would have been without any area change. My wave adjustment scheme for P-U continuity was designed to give precisely this equilibrium situation immediately on the area change. The Maeda model, though formally different, in this particular test happens to give exactly the same result. The Strube model, on the other hand, gives even stronger transients than the static one, and so does the adjustment for f-v continuity (but not the same!). This does not disqualify these models as such, but it suggests them to be particularly sensitive to undersampling of the area data.

The static flow wave model, the Maeda, and the continuous P-U model have the idiosyncrasy that when area is taken towards zero, the net flow is not interrupted. This is the consequence of continuity of flow and is mathematically all right, a finite flow can well go through an infinite impedance.
Fig. 2. Layouts of model test situations.

a. Shutter test. Three tube sections, terminated without reflections and externally fed with pseudo DC signals. Area of middle tube is altered in steps.

b. Squeeze test. Eight section line terminated by open and short circuits is gradually perturbed into a narrow and a wide half, and back. The lossless line is pre-excited with a standing wave on one of its resonance frequencies. To the right, resonance patterns in spectrogram style.

Fig. 3. Output from shutter test of Fig. 2a. The area of the middle tube is varied stepwise as shown in the top trace. Then follow net flow and pressure in that tube for the static model, for the Maeda and Strube models, and for the proposed wave adjustment models.
Uniform expansion test

The next two tests are staged in an eight section system, terminated at both ends with a reflection coefficient of -1, that is, closed in one (the glottal) end, and open, acoustically short-circuit, in the other. Initially the line is set up with an odd number of quarter periods of equal forward and backward waves. We thus simulate a lossless resonator tube, pre-excited to operate at one, but only one of its four resonances.

Test number two is to let this pre-excited system have tubes of equal areas that uniformly expand exponentially with time. Since areas are equal all reflection coefficients are zero except at the ends. The initially set up waves will oscillate back and forth indefinitely in a standing wave pattern without attenuation. From energy considerations we would expect the flow to rise and the pressure to fall exponentially with the area, but with half the exponent.

In the uniform expansion test all the dynamic models behave very closely like this but none identical to any other. For instance, an area increase of 5% per sample interval, repeated 128 times (a total area growth more than 500 times) gives quite insignificant differences in amplitude and phase, to the order of a few percent.

Conversely, the static model does not work at all. In this, nothing will happen to the partial waves because of the expansion. Thus, in the pressure analogy the pressure is constant while the flow increases with the area, and in the flow analogy, the flow is constant while the pressure is inversely proportional to area (cf. Eq. (1)).

Squeeze test

The third test could be called the 'squeeze test'. It uses the same lossless, pre-excited eight tube line. Initially all sections have unit area. During the test the area function is gradually perturbed to become narrow at the glottis end and wide at the mouth end, and then back to the original shape again. The four segments at the 'glottis' end are uniformly made narrower and the other four correspondingly wider so that the total volume is constant. Fig 2b shows the area function and corresponding formant trajectories in a schematic form.

The squeeze test illustrates a somewhat academic theorem not generally thought of in speech work. It applies to linear multi-mode resonant systems like strings, membranes, cavities, that are subject to slow, continuous changes of shape, and without external energy exchange. It can be named the principle of mode isolation, a consequence of the resonance modes being orthogonal.

When a resonator, freely oscillating in a resonant mode, is slowly perturbed, then the oscillating energy is confined to that same mode.
The frequency of this mode may well change as a consequence of the perturbation, the point is that the oscillations of the mode considered do not excite other modes, lower or higher. For a mode to be isolated this way, it is obviously required that the system is linear, and that perturbations are slow enough that they are insignificant within the period of one oscillation. Otherwise harmonics will be generated that will excite other modes as well. Conversely this principle could work as a test on physical accuracy in the models.

Fig. 4 shows results from the 'squeeze' test on the static and all the dynamic models, for pressure wave, and flow wave analogy. Time waveforms shown are the flows in tube 8, supplemented with successive Fourier spectra of the flow signal, weighted with a Hanning window. It is obvious from the spectra that all the dynamic models adhere to the mode isolation principle, and that the static model does not. Also the static model again differs greatly in the pressure and flow analogies, while the dynamic models are independent of type of analogy.

During the perturbation the first two formant frequencies approach until they differ only a small fraction of the total frequency range. Still the dynamic models manage to keep the neighbor modes 'uncontaminated' from the excited one. The corresponding holds also when the system is pre-excited to its higher modes. (In the limit of a total closure in the narrow half line the formants would have pairwise coincided, making mode isolation impossible.)

The physically reasonable situation at maximal perturbation would be that virtually all energy is squeezed out from the narrow half line into the wide one. Energy conservation then requires the mouth flow to be twice its unperturbed value. The Strube model and the model of f-v continuity adjustment are the only ones to manage this aspect correctly. The Maeda model and the P-U adjustment give little change in the mouth flow amplitude (as opposed to the uniform expansion test), they generally are under-sensitive to the area perturbation. This appears to illustrate the importance of conserving longitudinal momentum to insure the proper longitudinal transport of energy.

Recursive filter compared

Parenthetically I could mention a similar experiment that fails in mode isolation. It was done on a cascade of four second order formant resonators implemented as recursive z transform filters, a classical formant speech synthesizer. The lossless resonators were artificially pre-excited for stationary oscillation on F1, and then one formant frequency was perturbed. The output gets strong 'leakage' of signal into F2 either it is F1 or F2 that is perturbed. The reason is that the filters are derived from assumptions of a static system, so all kinds of artifacts can and will occur when the filter coefficients are changed in presence of a signal. There is also an inherent asymmetry in the system since the signal goes in one direction only. The first resonator is isolated from what happens in the later circuits, but the opposite is not true.
Fig. 4. Outputs from squeeze test of Fig. 2b. Top trace is area of sections 4-8. Then follow flows in section 3 as they develop in time for the different models as indicated. To the right are Fourier spectra of overlapping 48-sample intervals, using raised cosine (Hanning) window. Consecutive spectra are displaced 24 samples in time and 20 dB in level.

The static model gives very different waveforms for the flow and pressure partial wave analogies (two top waveforms), and in both cased energy is transferred to F2. The four dynamic models all keep the energy in F1, and each gives the same waveform with either flow or pressure partial waves.
This raises the philosophical conclusion that it is not feasible to
develop a dynamic version of the classical cascaded formant resonator
filter. It is additionally required that a feedback path is included, a
feature inherent in wave filters, of which the line analog is an
example.

Undersampling the area function

For computational economy one would like to update areas and re-
flexion coefficients at intervals much longer than the sampling inter-
val, to undersample the area function. The correspondent with formant
and LPC synthesis, to undersample formant and bandwidth data, has always
been practised successfully. Theoretically it is not permissible at
all, but it is motivated from these data being pseudo stationary. There
will, however, be artifacts in the synthesized output, like clicks or
harshness. The classical way to minimize the artifacts applies to
voiced sounds only, that is, to update formant data pitch synchronously,
when the oscillating energy is minimum, just before the major excitation
at glottal closure. This trick is just as applicable to the line ana-
log, but can hardly be performed when most needed, as when synthesizing
consonantal transitions.

Fig. 6 shows what happens in the squeeze test when areas are up-
dated every seven sample intervals, and in correspondingly larger steps.
It is obvious how the waveforms are severely distorted.

From several runs of the squeeze test with area undersampling, my
typical observations are: 1. The most prominent distortions and accompa-
nying mode leakages occur when the downsampleing ratio coincides with
low multiples or sub-multiples of the number of line segments; the
artifacts then tend to accumulate in phase. 2. The Maeda model and the
adjustment for continuous P-U give typically 10 dB lower mode leakage
than the other models. These other, including the static, do not show
very significant mutual differences in this respect. 3. Again the
static model gives very different waveforms for the flow and the pres-
sure partial wave analogy. Each of the dynamic models give essentially
the same result with either type of analogy.

Test conclusions

For a very rapidly changing area, like the glottis, then area
undersampling is out of question, and the Strube model or the f-v ad-
justment would be appropriate. For the slower area changes in the vocal
tract area undersampling can be used with some care, and then the Maeda
model or the P-U adjustment are preferred to minimize spurious tran-
sients. A consequence will then be that the dynamic effects will be
under-represented. More specifically, the changes in formant bandwidths
due to dynamic area change will not be as large as they should.

Probably this is not very important, as was shown with a simple
resonator example by Fant (1980). Concurrent tests by Meyer & Strube
(1984) also seem to indicate the effect to be perceptually marginal.
For the bandwidth contribution to be significant the relative area
Fig. 5. A parallel to the squeeze test, but using a classical cascade formant filter, F-pattern at top. A greater part of the energy is transferred to $F_2$.

Fig. 6. Same as Fig. 4, but with area data under-sampled by a factor of 7 as seen from the notches in the area trace at top.

All models show energy leakage to higher formants, but the P-U adjustment and the Maeda model generally less than the others. Details vary considerably depending on the factor of undersampling.
change must be fast, something that can happen only with small areas close to cutoff, the typical situation is the release of an occlusion. A balancing factor is that when the area is small, the laminar and, perhaps even more, the jet losses are large. The point is, that for the bandwidth term from the area change to overrule that of the resistive loss, there is very little time available, up to a few milliseconds.

The different scattering models have also been applied to a rapidly varying tube to model glottis. Then naturally the ones based on continuity in flow cause severe problems when flow is to be interrupted, while the Strube and f-v adjustment work well. So does, amazingly enough, the static pressure wave analogy. This is because of the specific area conditions here, the glottal area is always small compared to the neighboring areas. Because of that the dynamic corrections happen to come out as negligibly small with the dynamic pressure analogies.

The different models have also been applied to a rapidly varying tube to model glottis. The naturally the ones based on continuity in flow cause severe problems when the flow is to be interrupted, while the Strube and f-v adjustment work well. So does, amazingly enough, the static pressure wave analogy. This is because of the specific area conditions here, the glottal area is always small compared to the neighboring areas. Because of that the dynamic corrections happen to come out as negligibly small with the dynamic pressure analogies.

References


