Real-time Wave Separation in a Cylindrical Pipe with Applications to Reflectometry, Echo-cancellation, and a Hybrid Musical Instrument

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Abstract: Backward and forward propagating waves in a short cylindrical pipe are separated in real-time by means of an array of 5 microphones, a high-precision analog circuit, and a real-time numerical post-treatment. The separation factor exceeds 40 dB over several kHz. The theoretical limit at high frequencies has been reached experimentally. One application consists in reflectometry without use of the long pipe normally required. Associated with a digital signal processor (DSP), wave separation also permits to efficiently cancel the wave reflected by one end with one control-loudspeaker, whose transfer function has been inverted and implemented in the DSP as an IIR filter. Finally, a musical application of the system to a hybrid wind-instrument is presented.

INTRODUCTION

Applications with active control of sound consist in minimizing some acoustical quantity, usually after an adaptative process. As the acoustical field can seldom be expressed analytically, the time constant of the process considerably exceeds any characteristic period or pseudo-period of the acoustical signal. In the making of a hybrid flute-like musical instrument, one should by contrast achieve a very fast control of sound, with a large dynamics, but inside an acoustical duct that can be as simple as a cylindrical pipe. The hybrid flute consists in a normal mouthpiece connected to a short pipe, closed by a control-loudspeaker. In other applications of the wave separator presented below, or at the calibration stage, the mouthpiece may be replaced by an excitation-loudspeaker (Fig. 1). The tube – which has no open side holes – is equipped with microphones and the control-loudspeaker is driven by a DSP board. In order to control the acoustical waves inside the tube, one should a) separate the forward and backward propagating waves, b) cancel the waves naturally reflected by the control-loudspeaker (considered as a passive device), and c) generate a reflected wave in accordance to a prescribed reflection function.

This has been done by a combination of analog circuitry and real-time computation by the DSP (TMS 320C30). In this scheme, the absence of the adaptation process usually found in active-control standard designs is made possible by the simplicity of the propagated acoustical field.

METHOD AND EXPERIMENTAL SETUP FOR THE WAVE SEPARATOR

Five microphones are inserted in the wall of the cylindrical pipe, such as not to change the internal geometry of the pipe (Fig. 1). The acoustical pressure at the k-th microphone (2 ≥ k ≥ -2) is the summation of the forward and backward propagating plane waves, with opposite delays $s_k(t) = p_f(t - kr) + p_b(t + kr)$ with $r = d/c$. 

[Diagram of experimental setup]
It could also be expressed as a Taylor development of each separate wave, as a function of space. Making use of the plane wave properties and inverting the development written up to the 4th order leads to:

\[
\frac{\hat{\Phi}_f - \hat{\Phi}_b}{\hat{\Phi}} \approx \frac{1}{r} \left( \frac{2}{3} \frac{s_{-1}}{s_{-2}} - \frac{1}{12} \frac{s_{-2}}{s_{-1}} + \frac{1}{12} \frac{s_{+2}}{s_{+1}} \right)
\] (1)

An estimate \( \hat{p}_f \) of the forward propagating wave is obtained by integrating Eq. (1) and summing the result with the acoustical pressure at the central microphone \( s(t) = p_f(t) + p_b(t) \). This wave separator is the generalization of a two-microphone intensimeter and has been implemented with an analog circuitry.

One can qualify its performance in Fig. 2 by relating the estimate to the real quantities as \( \hat{p}_f = (1 - \alpha) p_f + \beta p_b \), where \( \alpha \) and \( \beta \) are both expected to be very small. They are identified as digital filters and implemented in the DSP, improving the performances with a post-separation process, still running in real time.

The spatial separation of the microphones limits \( F \) at high frequencies (\( \lambda/2 \) limit) whereas it is limited at low frequencies by the background noise in the time integrator.

**APPLICATIONS WITH AND WITHOUT ACTIVE CONTROL**

**Reflectometry** – This wave separator is an alternative to the method often used in reflectometry of using a very long pipe for splitting in time forward and backward propagating waves. Here, with a model of multiple reflections inside the short pipe and a preliminary calibration with known boundary conditions, one can use a continuous excitation and obtain the reflection function of a (linear) unknown pipe termination.

**Active control and the hybrid flute** – The reflectometry method has been used to characterize the control-loudspeaker by its reflection function. One can then build an echo-canceller by designing an IIR digital filter that matches the opposite response (20 coefficients are enough to obtain a good fit), implement the filter in the real-time DSP, and drive the loudspeaker by the DSP which receives \( p_b(t) \) as an input. Fig. 3 shows that the back-propagating wave in the pipe is largely canceled.

A musical instrument can be characterized by a given reflection function at a point close to the mouthpiece. In a similar way as above, one can implement this reflection function in the DSP by means of an additional IIR filter. The excitation loudspeaker is replaced by a mouthpiece, blown by a musician. The first hybrid flute that has been built operates in a range of an octave and exhibits the main characteristics of the instrument.