# Signal-Dependent Nonlinearities for Physical Models Using Time-Varying Fractional Delay Filters

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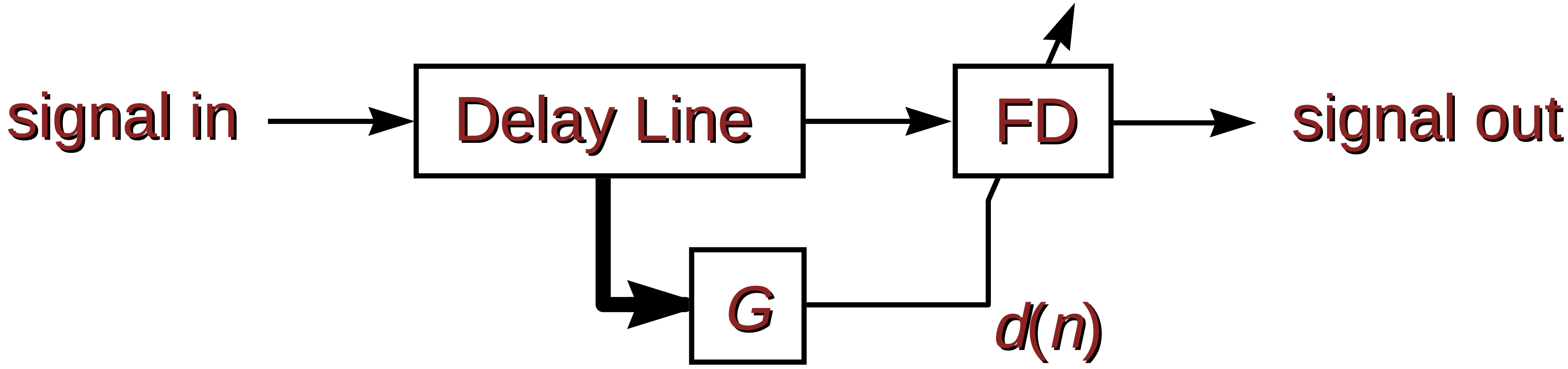
## Outline

- ➤ Introduction
- ➤ Nonlinearities of Musical Vibrating Structures
- ➤ Implementation of Time-Varying FIR FD Filters
- ➤ Synthesis Examples
- ➤ Conclusions and Future Work

# Introduction

- Nonlinearities have been discarded in physical modeling, when possible
  - plucked strings are linear -- wind instruments nonlinear
- Passive nonlinearity (Pierce and Van Duyne 1997)
  - Msallam *et al.* ISMA'97; Tassart *et al.* ICMC'97
- We show that passive nonlinearities can be generalized by using Time-Varying Fractional Delay Filters
- We suggest FIR FD filters for implementing passive nonlinearities

# General Signal-Dependent Delay Line




- Input signal controls the fractional-delay (FD) filter (see Laakso *et al.* 1996 for a review on FD filters)
- Function *G* computes $d(n)$ based on the delay-line signal
    - *G* may include delay, linear filter, or nonlinear function
    - *G* may be a many-to-one mapping

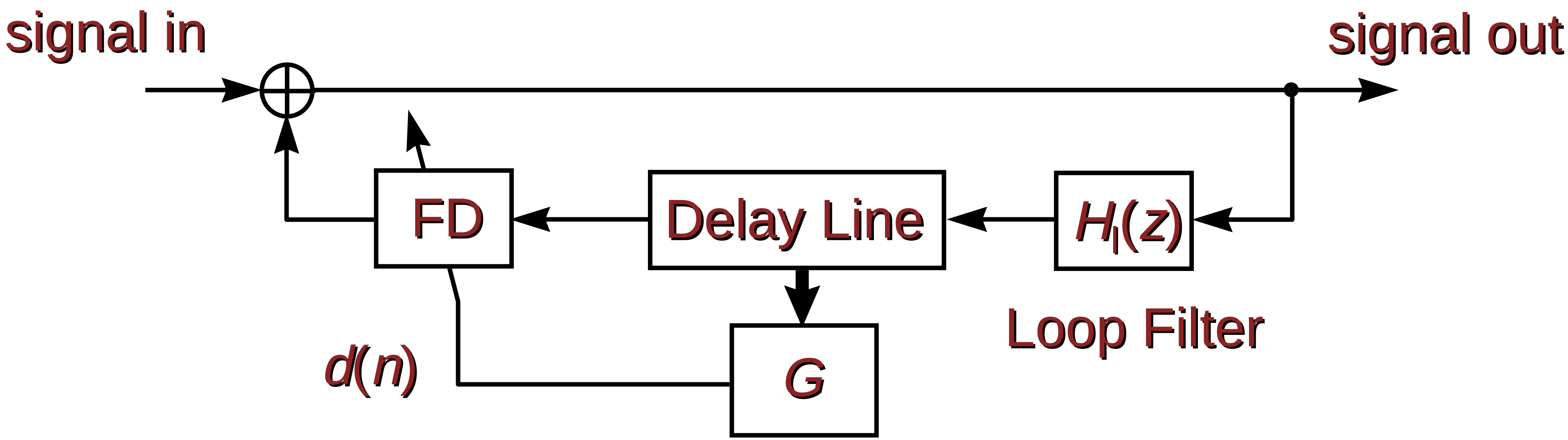
# Nonlinearities of “Linear” Resonators

- Three cases appear in literature:

1) Nonlinearities in brass instruments when amplitude is high (Msallam *et al.* 1997)
2) A nonlinear string termination by a double-spring apparatus (Pierce & Van Duyne 1997)
3) Large-amplitude vibration of a string causes modulation to its tension (Legge & Fletcher 1984; Karjalainen *et al.* 1993)

⇒ Fractional delay filter with signal-dependent delay!

# String Model with Passive Nonlinearity




- Basic string synthesis model (Jaffe & Smith, CMJ 1983; Smith, CMJ 1992; Välimäki *et al.*, JAES 1996)
- Extended with a signal-dependent fractional delay filter

# TVFD Based on Allpass Filter

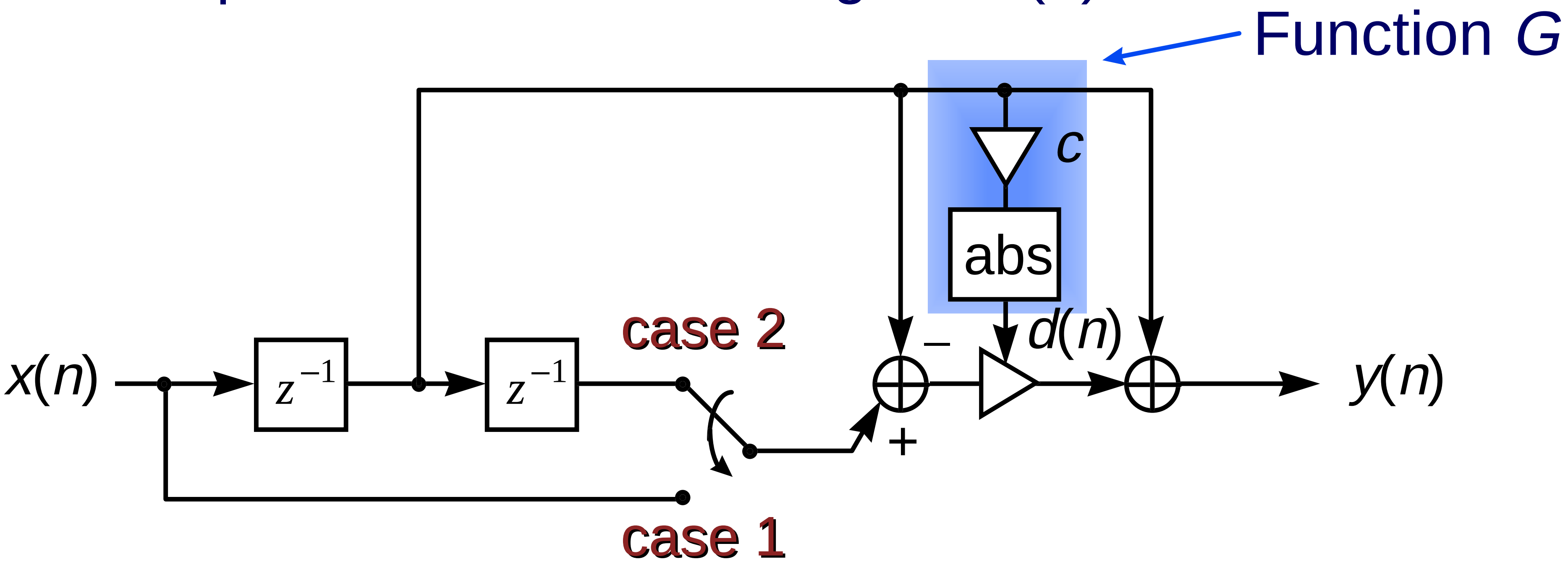
- Pierce and Van Duyne (1997) suggest a first-order allpass filter
- the value of filter coefficient $a_1$ is switched at the zero-crossing
- string synthesis with nonlinear features, such as generation of missing harmonics
- a feedback loop usually remains stable with this filter
- continuous variation of $a_1$ would cause transients ! (transient elimination is possible but expensive, see Välimäki *et al.* 1995, Välimäki & Laakso, 1998)

# TVFD Based on FIR Filters

- We suggest FIR fractional delay filters
  - a good choice is Lagrange interpolation (see also Tassart *et al.* ICMC'97)
- Delay parameter may be changed continuously!
- Disadvantage: magnitude response is not flat
- Properties of a TVFD filter must be easy to change
  - table look-up OR a special filter structure
- We use the Farrow structure of Lagrange interpolation (Välimäki 1995)

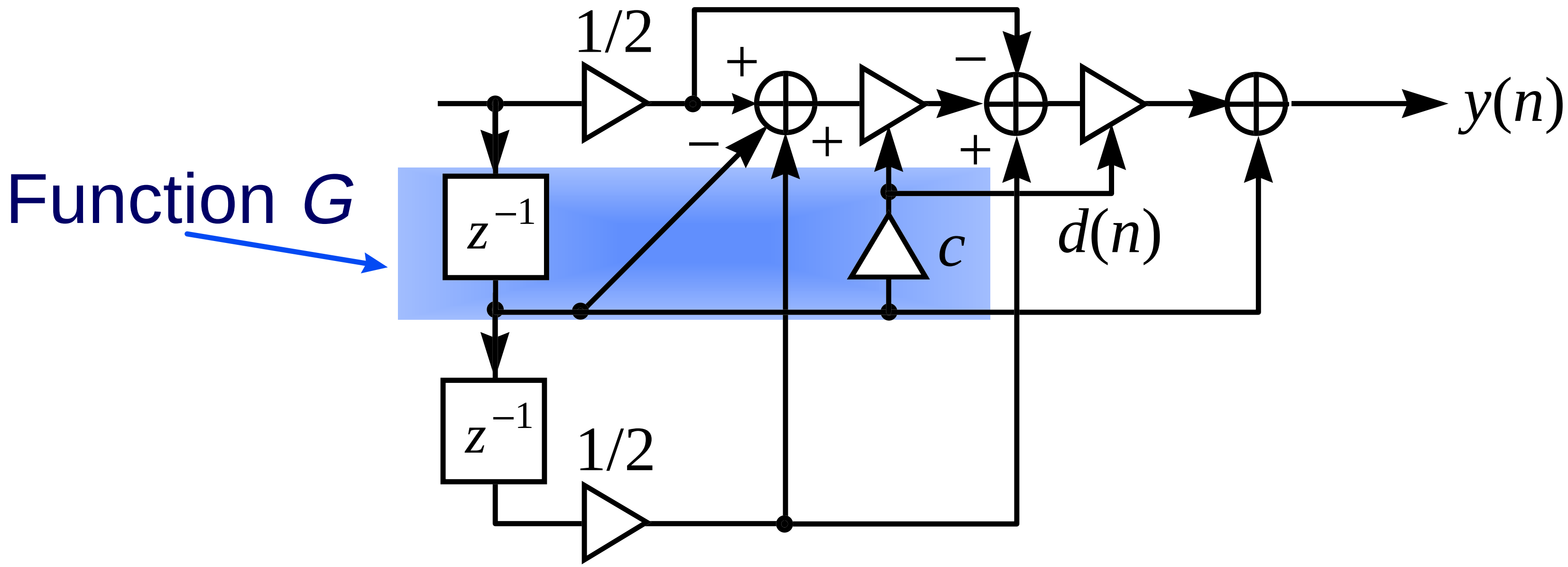
# Farrow Structures for TVFD

- Implementation of time-varying linear interpolation for delay values 1 - *d*(*n*) or 1 + *d*(*n*)
- multiplier *c* controls the range of *d*(*n*)



# Farrow Structures for TVFD (cont’d)

- Implementation of time-varying second-order interpolation for delays between 0 and 2 samples
- multiplier *c* controls the range of $d(n)$



# Synthesis Examples

1) linear string synthesis

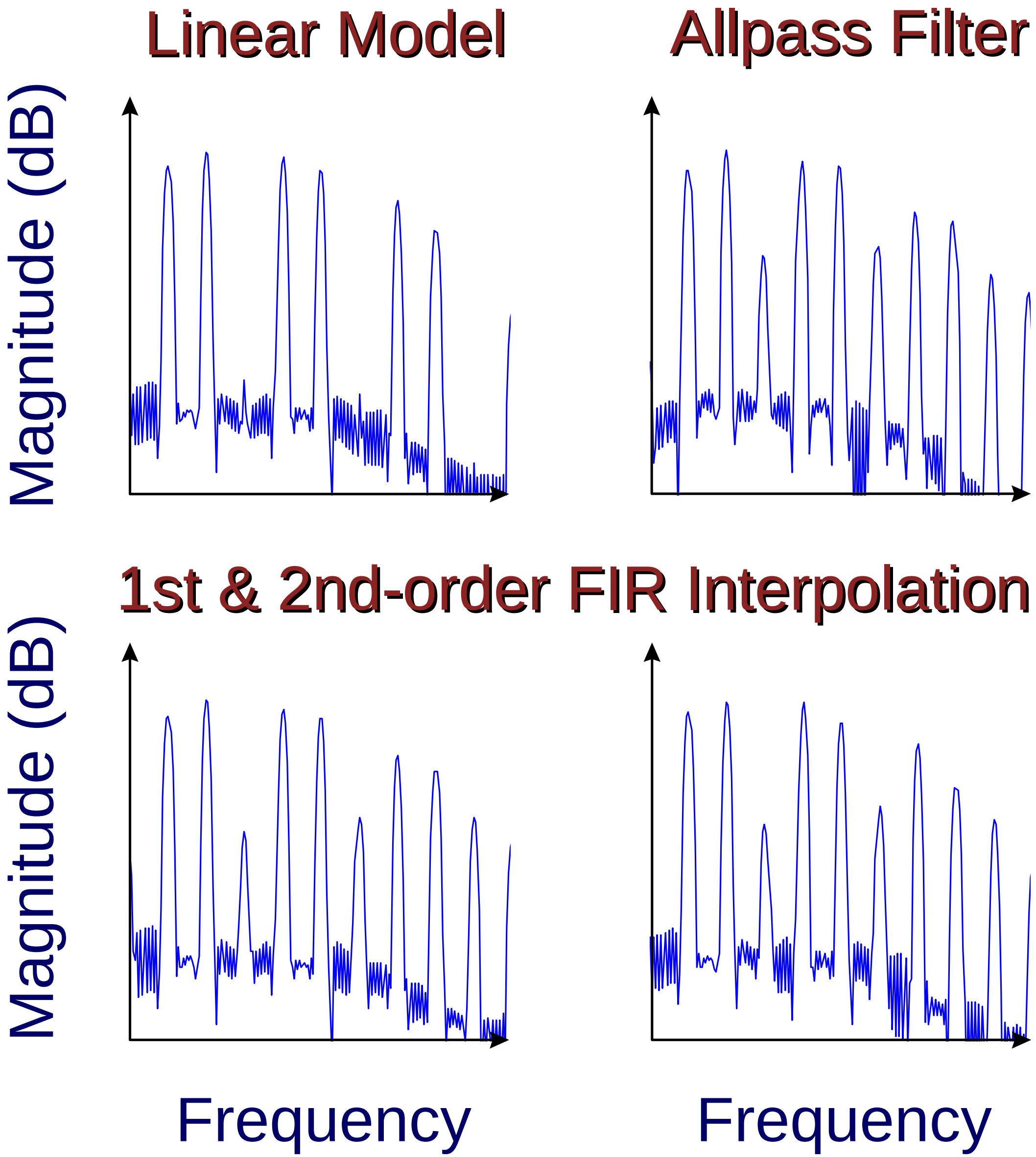
String synthesis with passive nonlinearity:

2) switching allpass filter (Pierce & Van Duyne)
3) first-order Lagrange interpolation
4) second-order Lagrange interpolation

- The delay parameter in cases 2), 3), and 4) is switched between 0 and 0.05 ($a_1$ = -0.0244)

# Comparison of Magnitude Spectra

- Missing harmonics are generated in all cases!
- Results with FIR filters are not identical with the allpass case but they are similar



# Efficient Simulation of the Nonlinear Vibration of a String

- In vibrating strings, tension changes as well as the wave propagation speed
- Distributed passive nonlinearity
- In Section 3.2, we show how this distributed phenomenon can be computed at a single point in a digital waveguide model
- Further details will be published later...

# Sound Examples

- Plucked-string synthesis including tension modulation implemented using signal-dependent FIR FD filters
  1) linear string synthesis
  2) tension modulation
  3) more tension modulation

# Conclusions and Future Work

- FIR fractional delay filters with signal-dependent coefficients for implementing passive nonlinearities in physical modeling synthesis
- Delay parameter may be changed continuously!
- Future work: detailed modeling of tension modulation in plucked strings
- See URL http://www.acoustics.hut.fi/