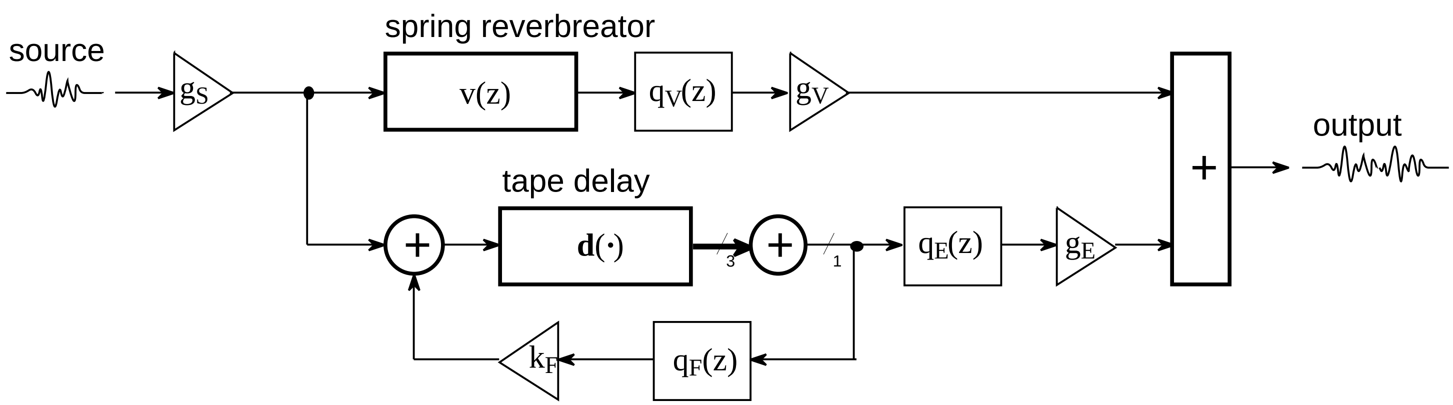
UNIVERSAL AUDIO

Digital Emulation of the Roland RE-201 SPACE ECHO

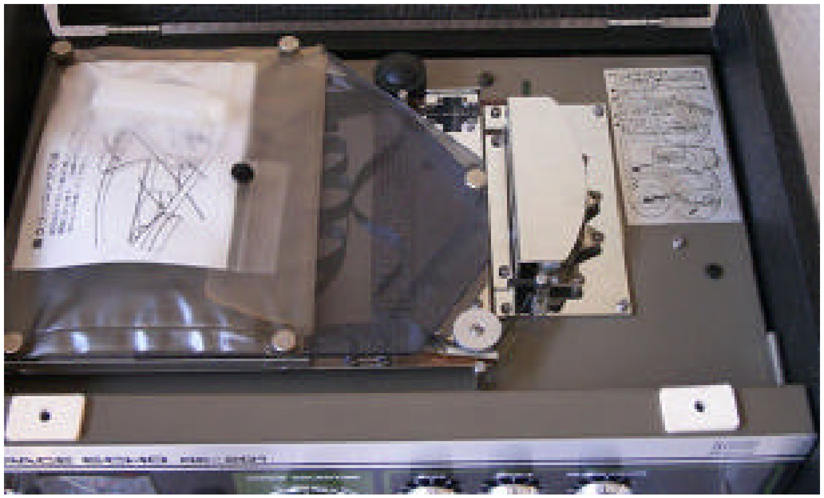
Jonathan S. Abel, David P. Berners

RE-201 Space Echo



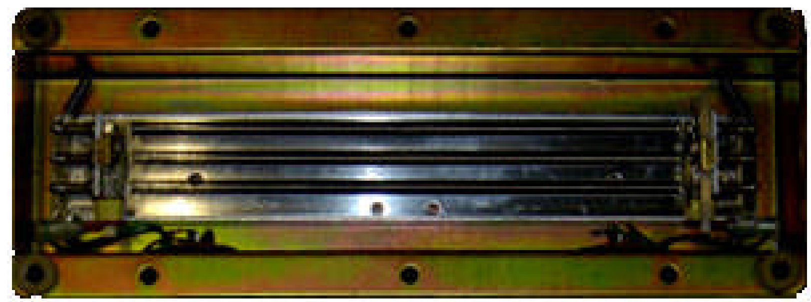
- **The RE-201 Space Echo has tape delay and spring reverb systems operating in parallel.**

Presentation Overview



RE-201 Tape Transport

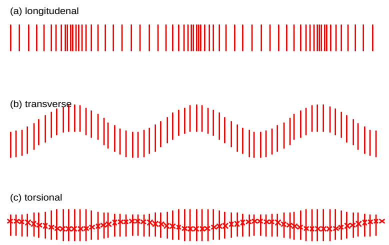
- **Tape Delay Emulation**
  - **Tape Delay Overview**
  - **Tape Transport Dynamics**
  - **Tape Loop Model**



Accutronics Type 8 Spring Tank

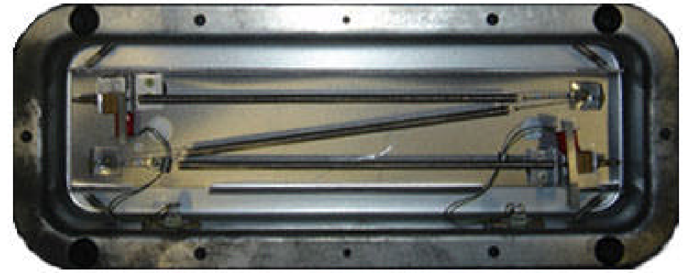
- **Spring Reverberator Modeling**
  - **Spring Reverberator Development History**
  - **Spring Wave Propagation, Dispersion**
  - **Waveguide Model and Parameter Tuning**

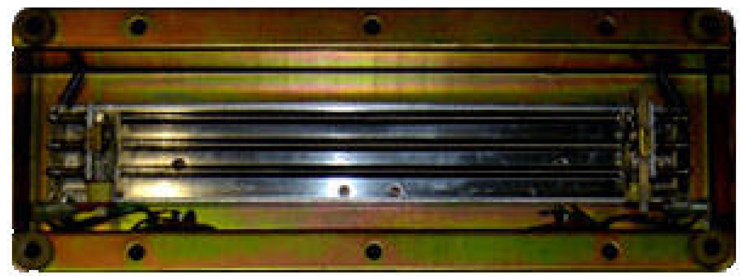
Spring Reverberation



spring propagation modes

Accutronics Type 8
Sansui RA-700



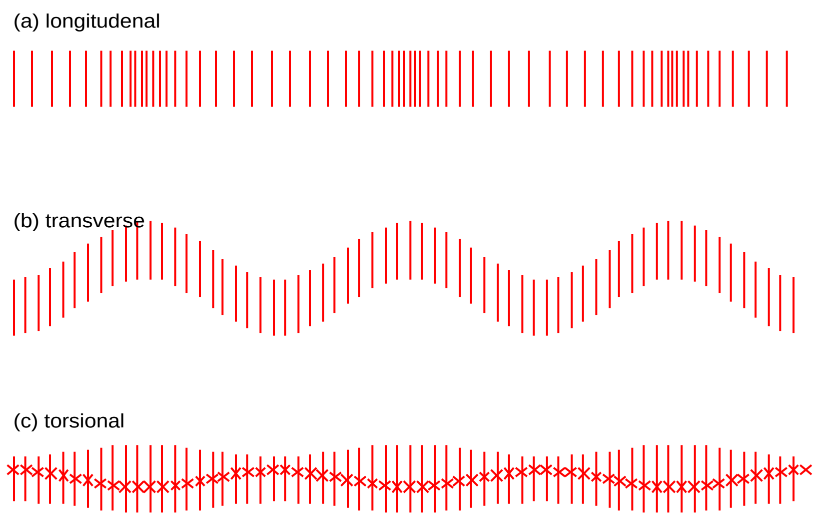


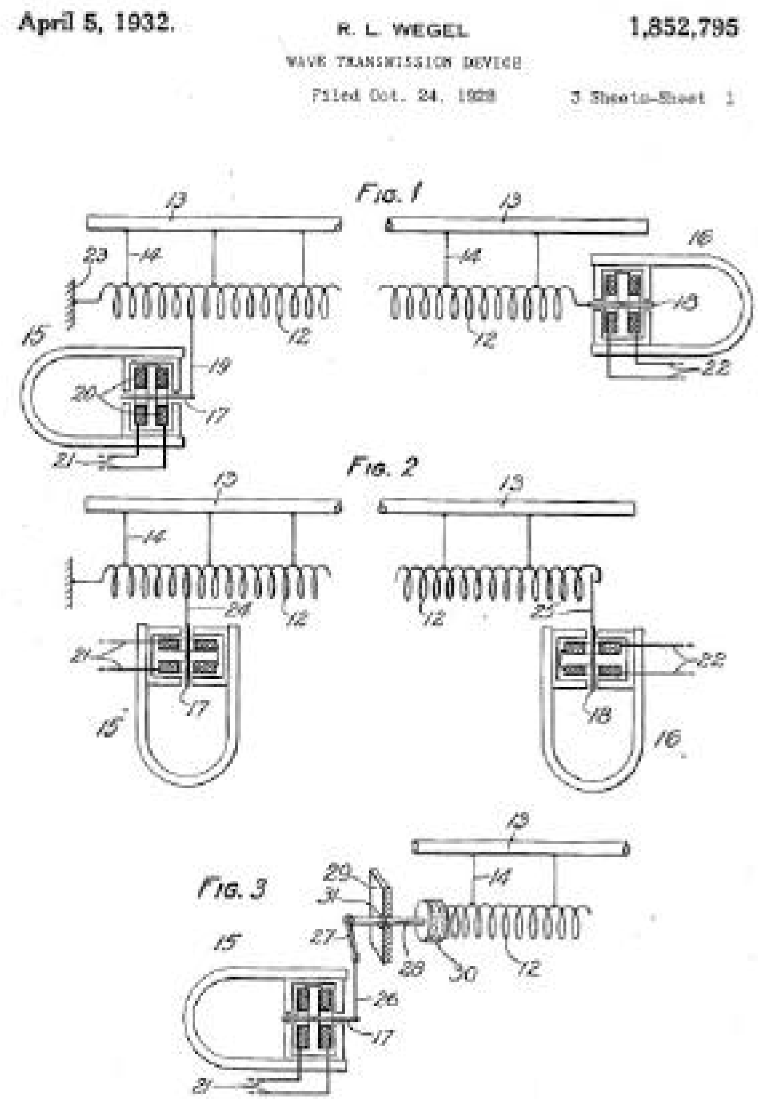
spring reverberators

dry wet

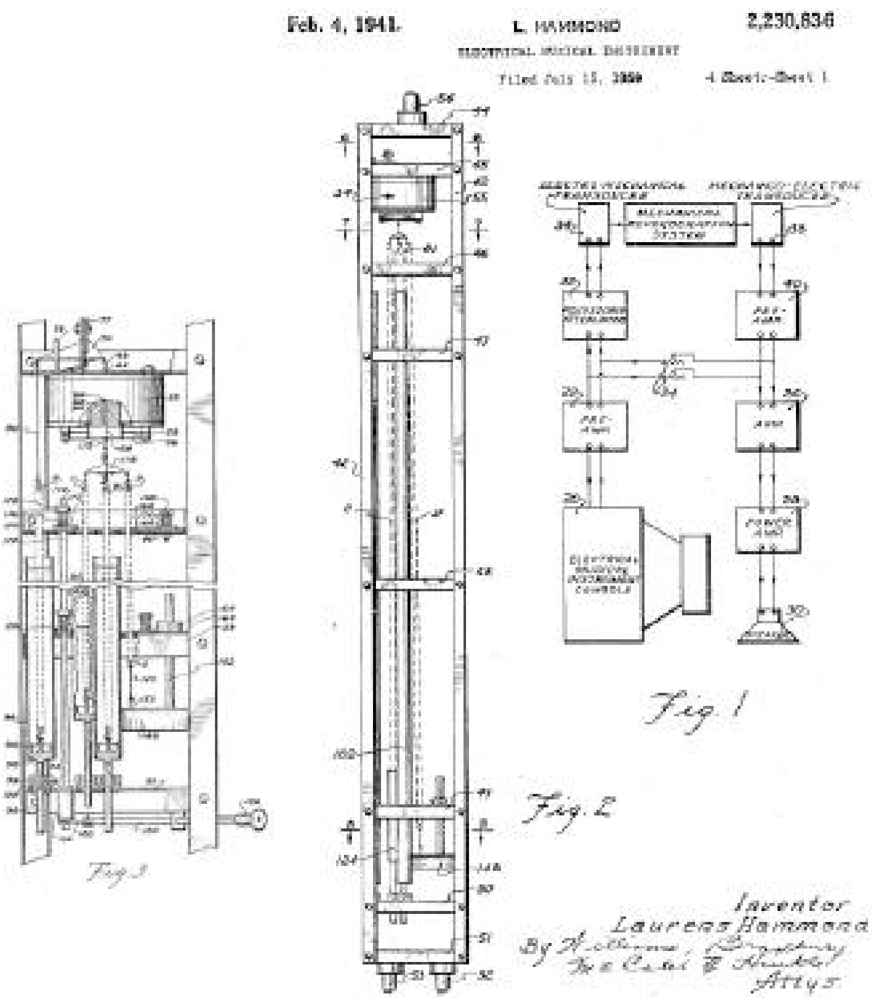
- **Helical coils support a number of audio-frequency transmission modes, and have long been used for delay and reverberation.**
- **Dispersive propagation gives spring reverberators a distinctive sound.**

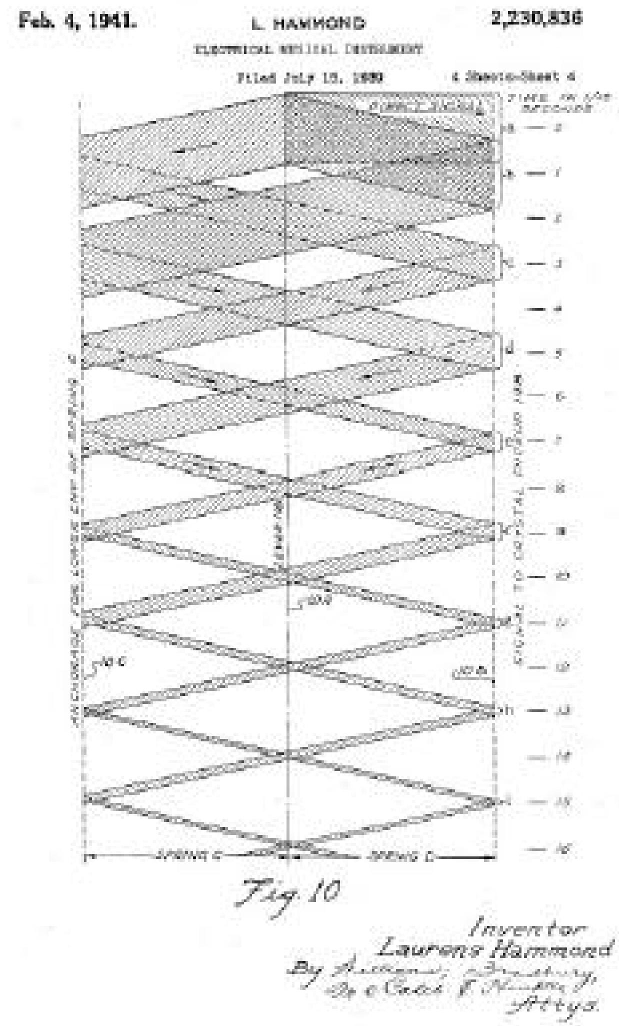
Spring Propagation Modes



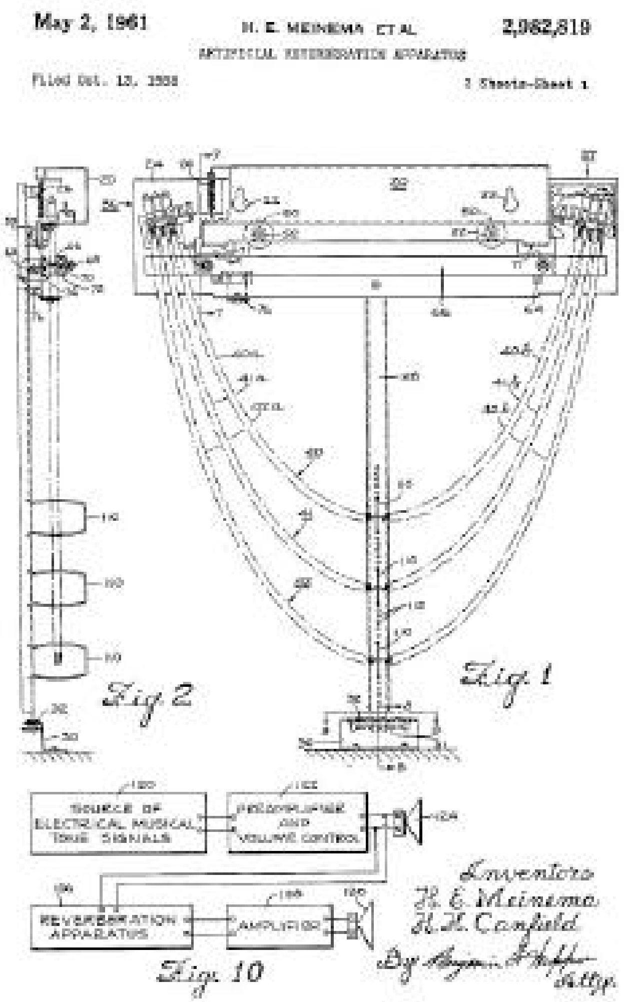


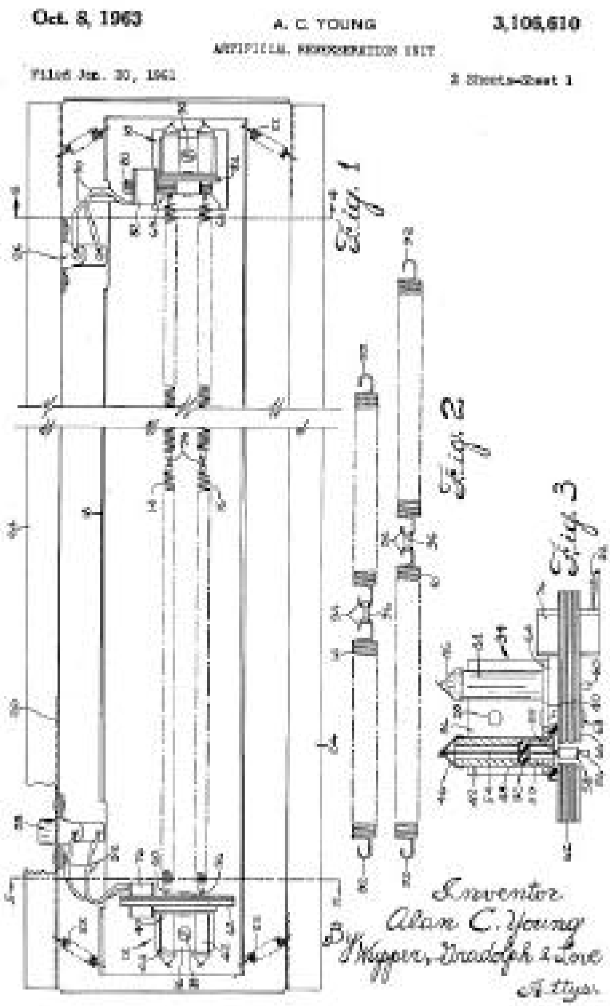
Hammond Spring Reverberator



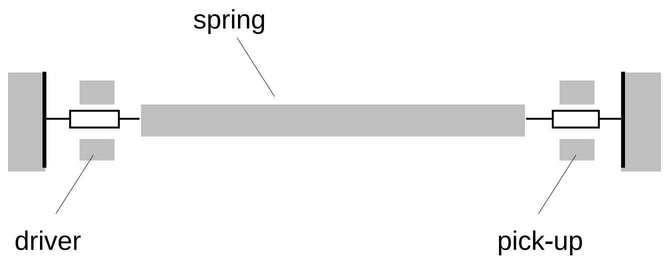


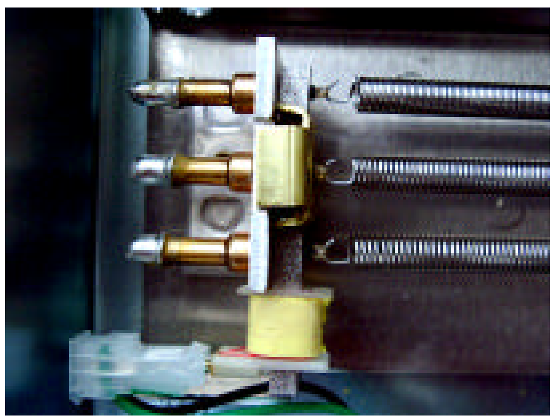
Meinema, Young Spring Reverberators

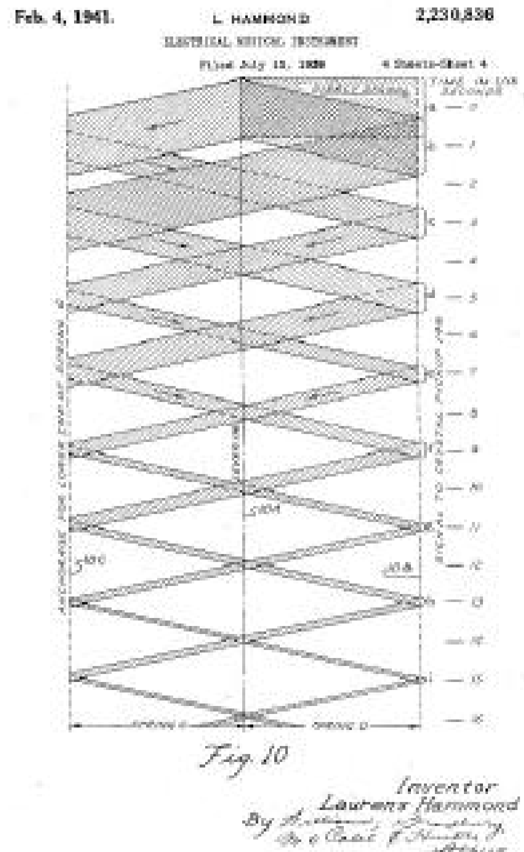




Wave Propagation

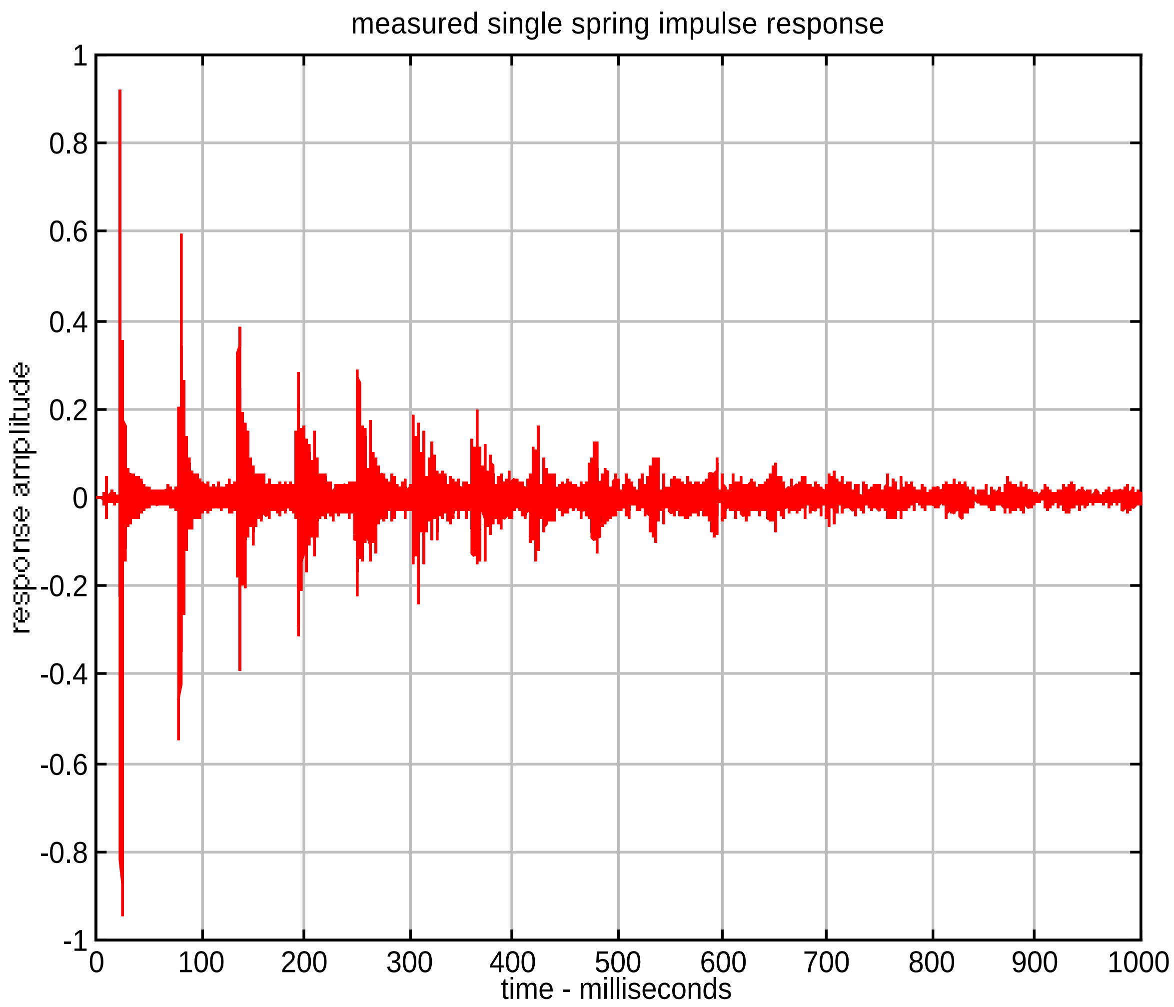




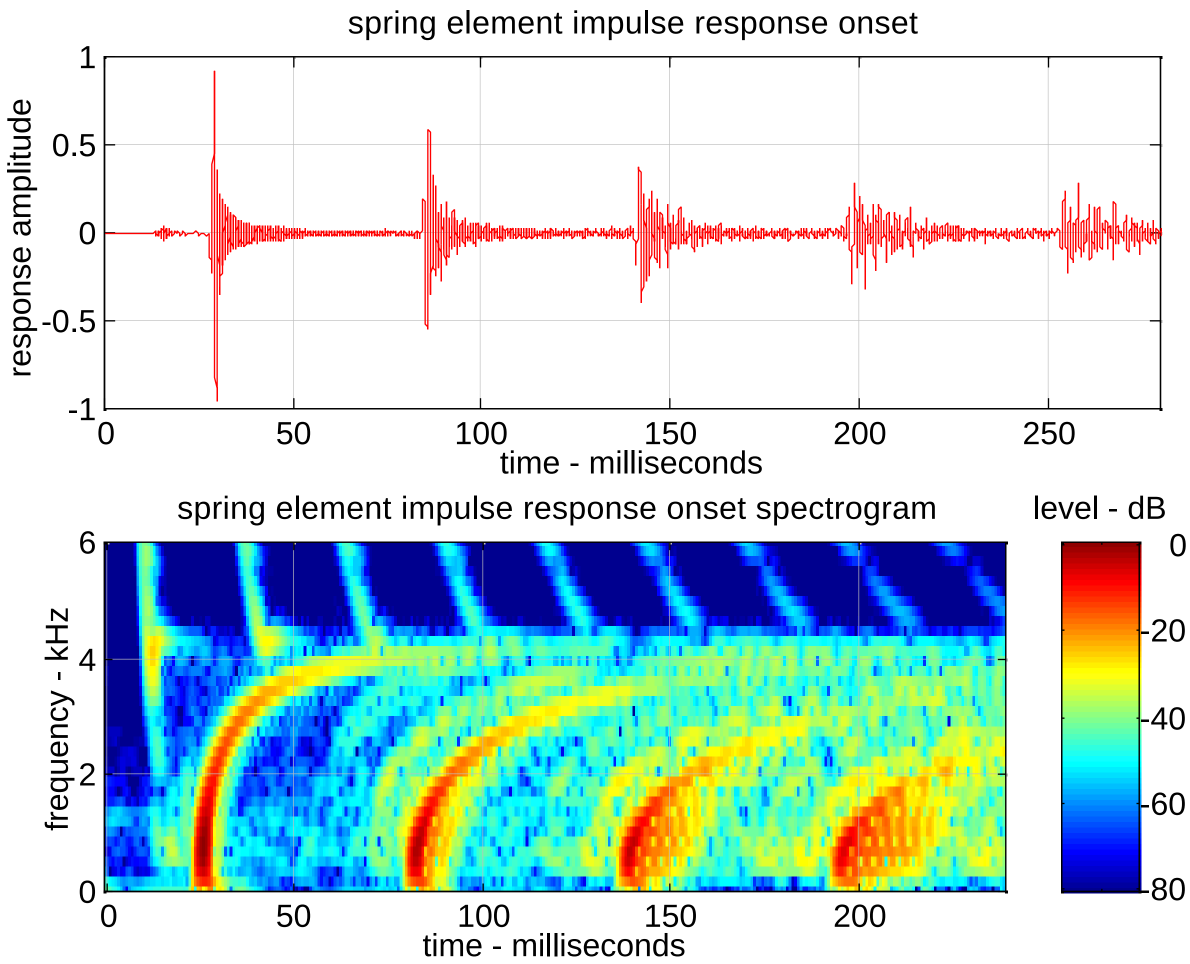


- **Torsional waves travel back and forth along the spring, reflecting off the supports, and creating a decaying series of echoes at the pick-up.**

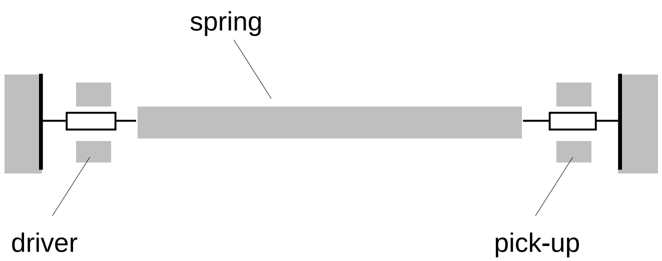
Spring Element Impulse Response



Spring Element Impulse Response Onset

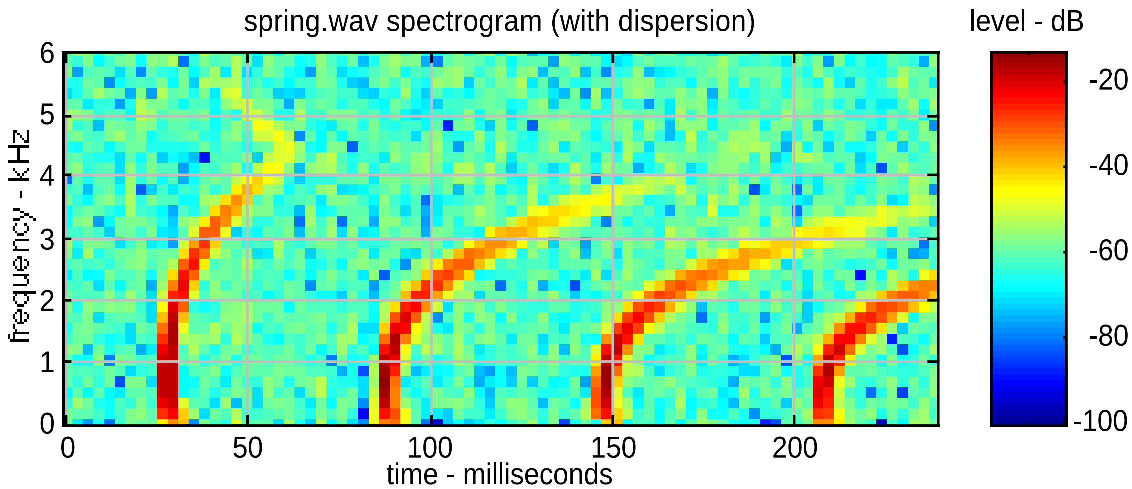


Dispersive Wave Propagation



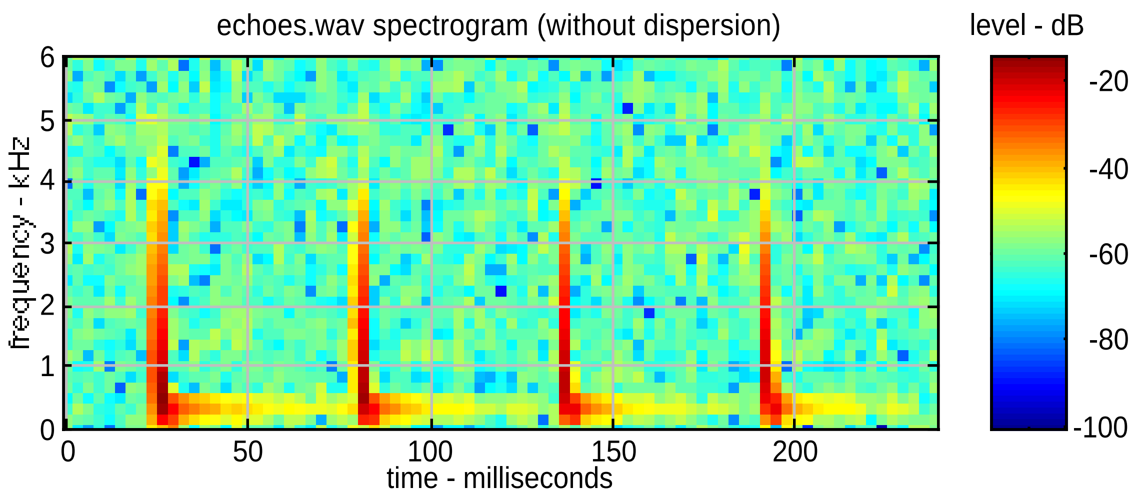
- **Torsional waves propagate dispersively, becoming smeared out as they travel.**

Dispersive, Nondispersive Echo Sequences



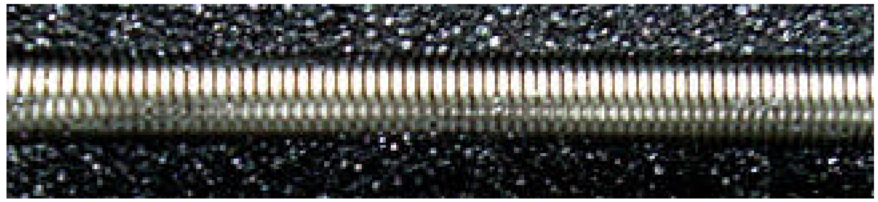
individual echoes

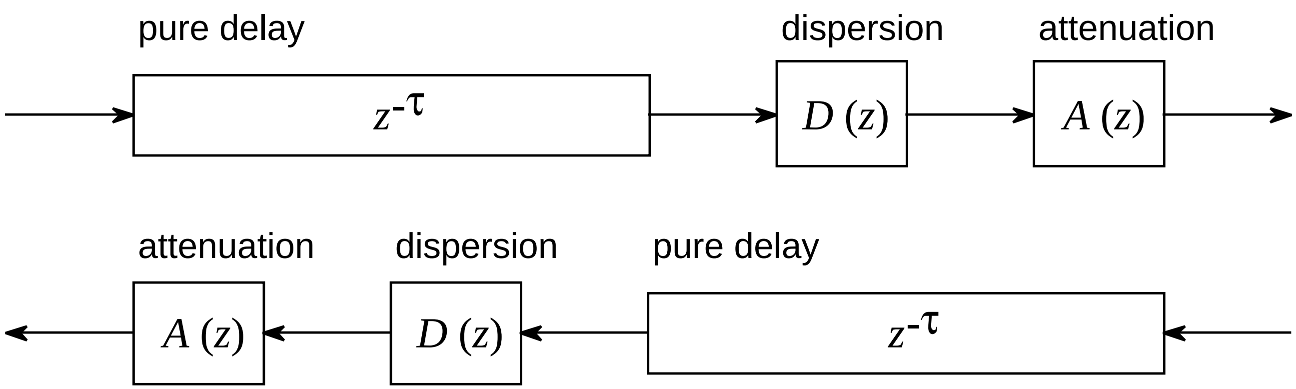
dispersive echo sequence



echo sequence

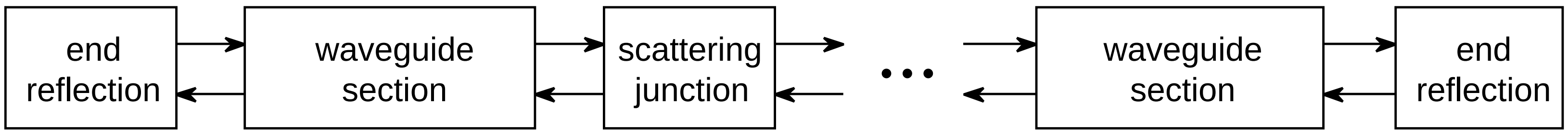
Waveguide Section

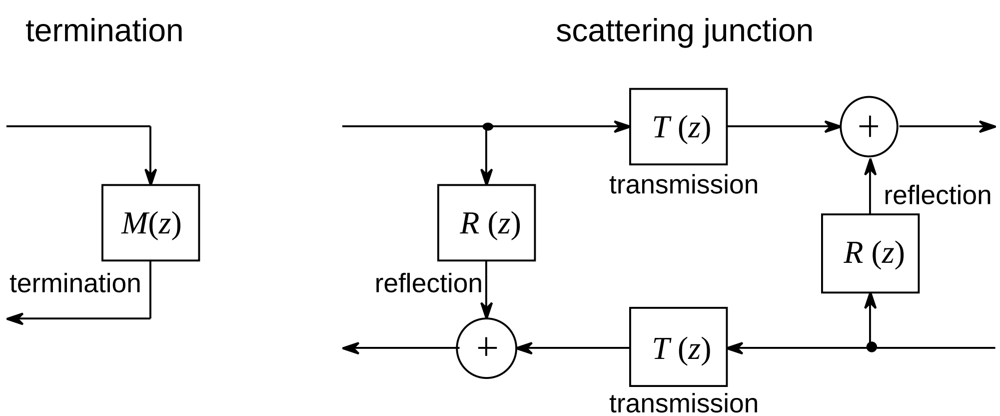


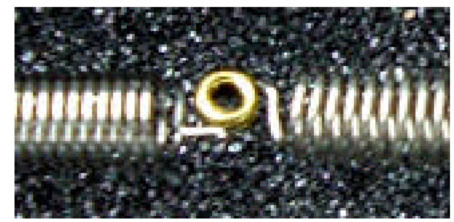


- **Left-going and right-going waves are separately processed via pure delay elements and commuted dispersion and propagation loss filters.**

Waveguide Spring Element Model

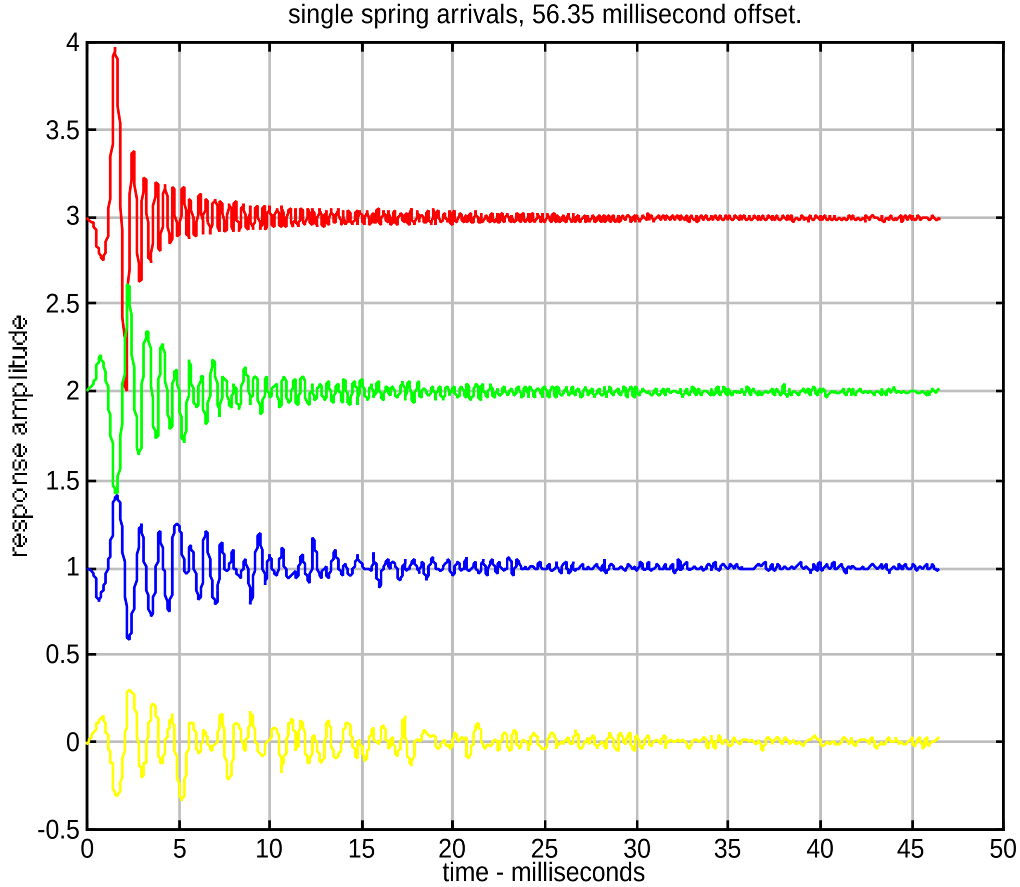


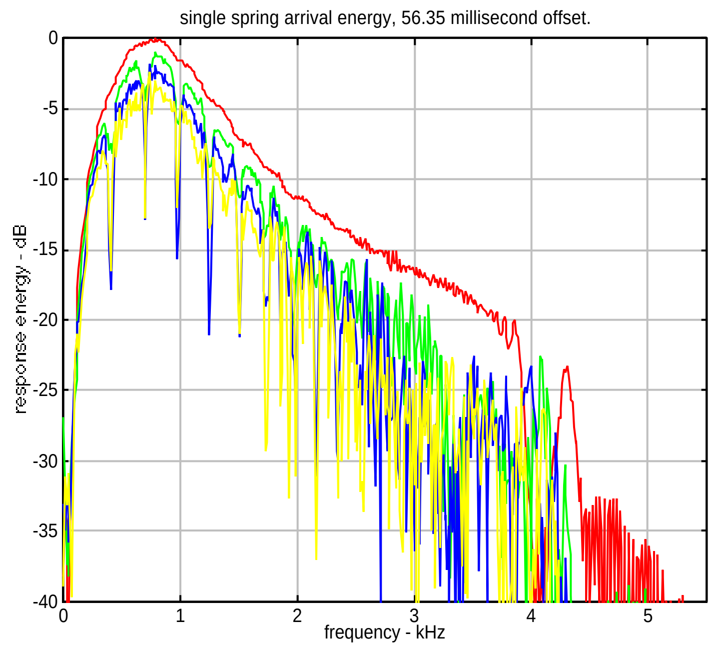




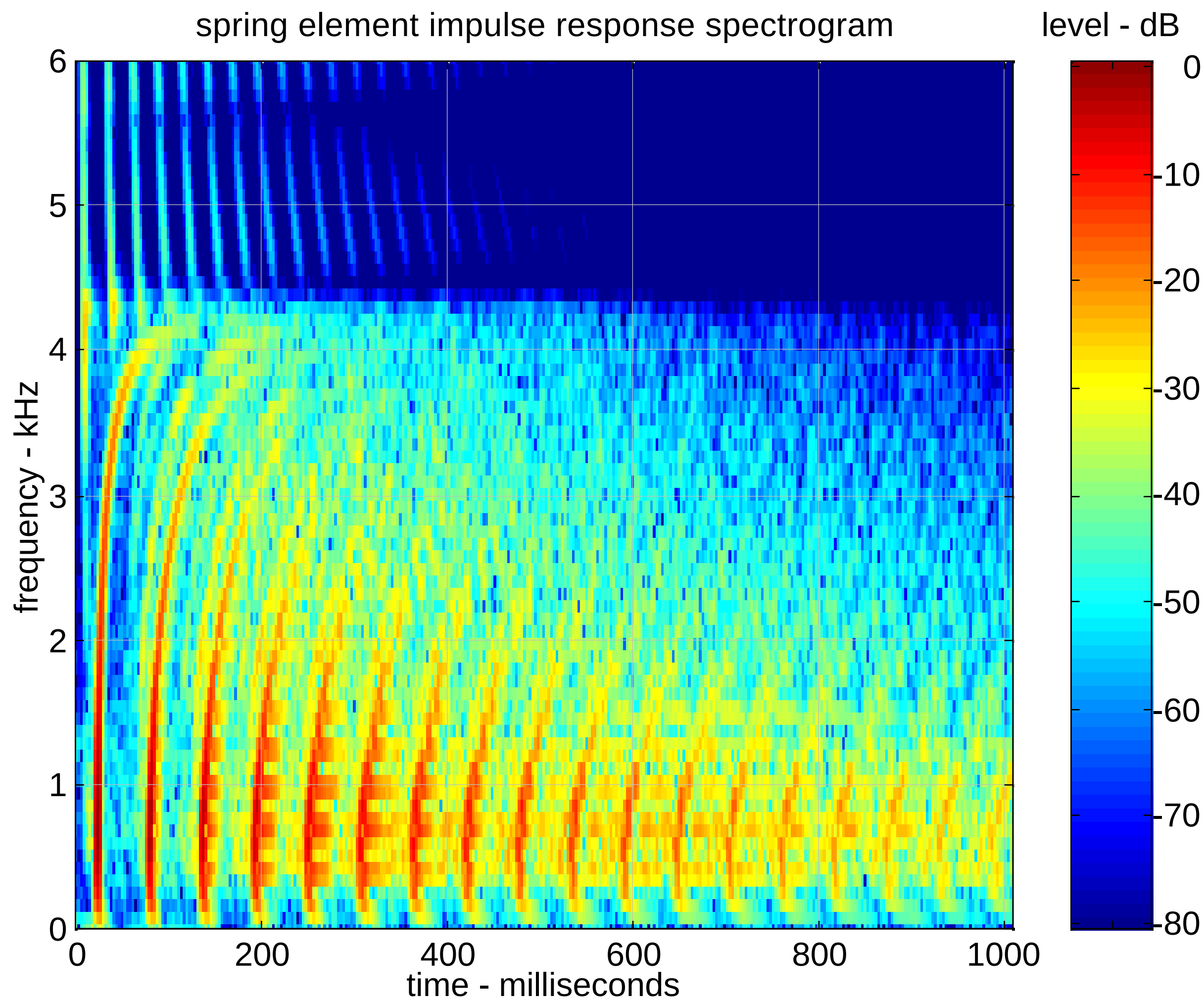
- **Each spring element is modeled using a set of waveguide sections, connected via scattering junctions, and terminated at the element ends.**

Spring Element Arrivals

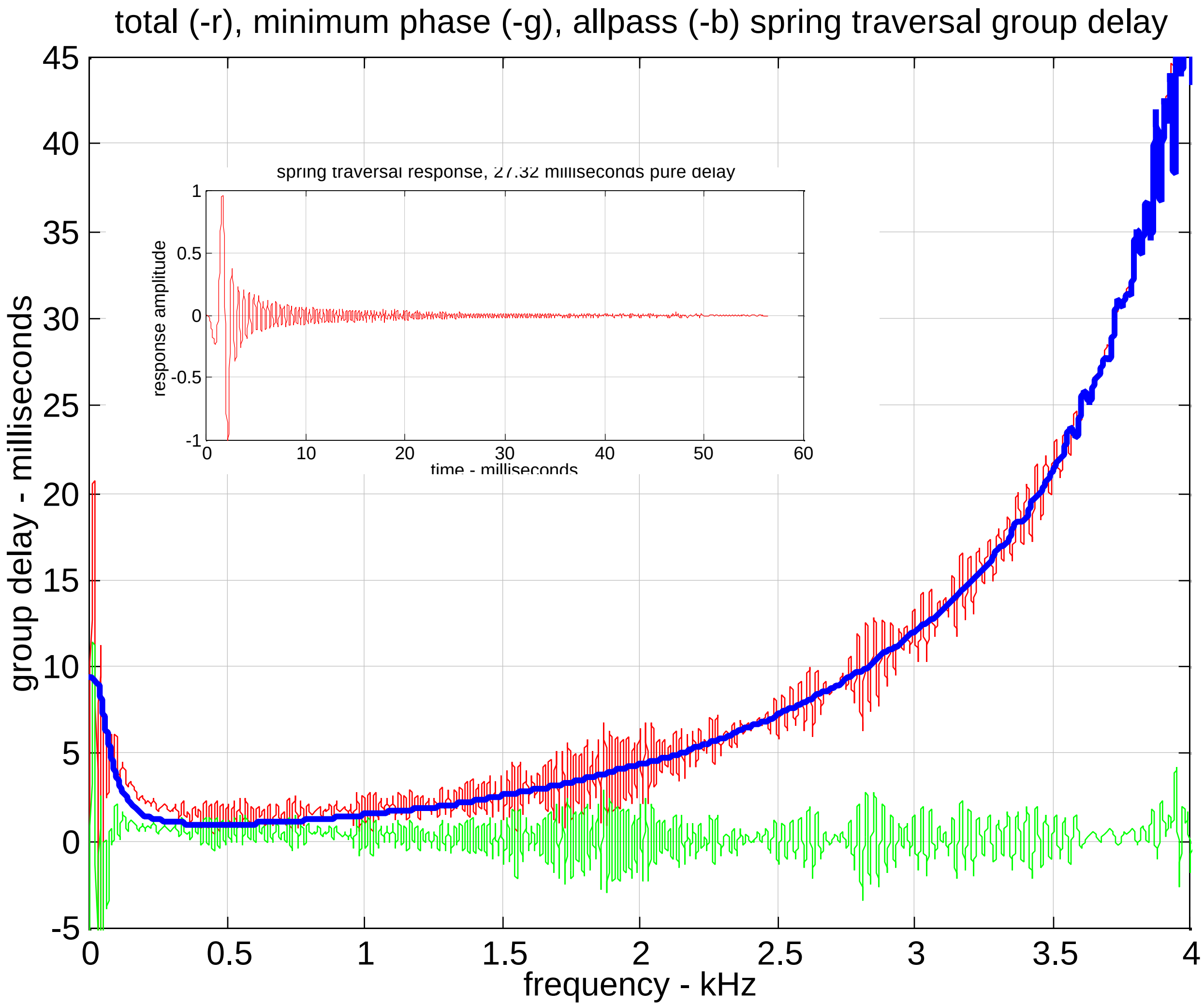




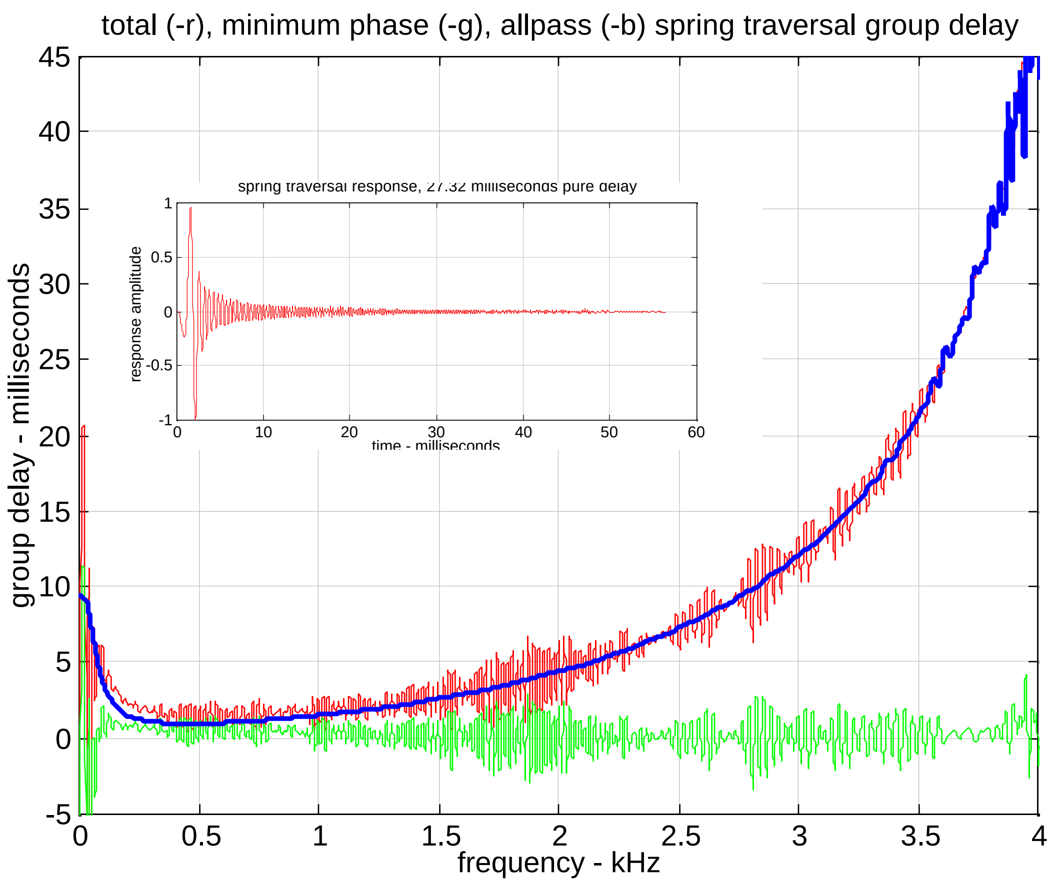
Spring Element Response Spectrogram



Single Traversal Dispersive Delay Estimation



Dispersion Filter Design



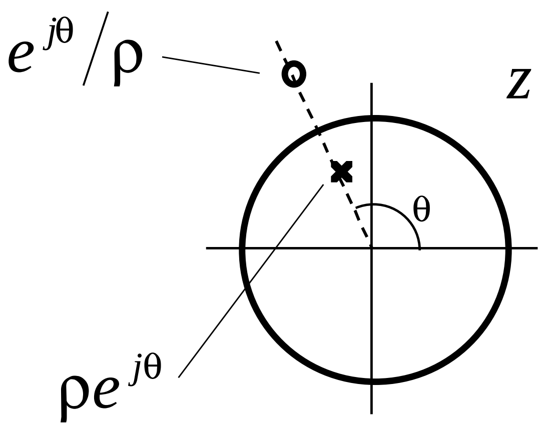
- **The dispersion filter is chosen to match the allpass component of the spring traversal group delay.**

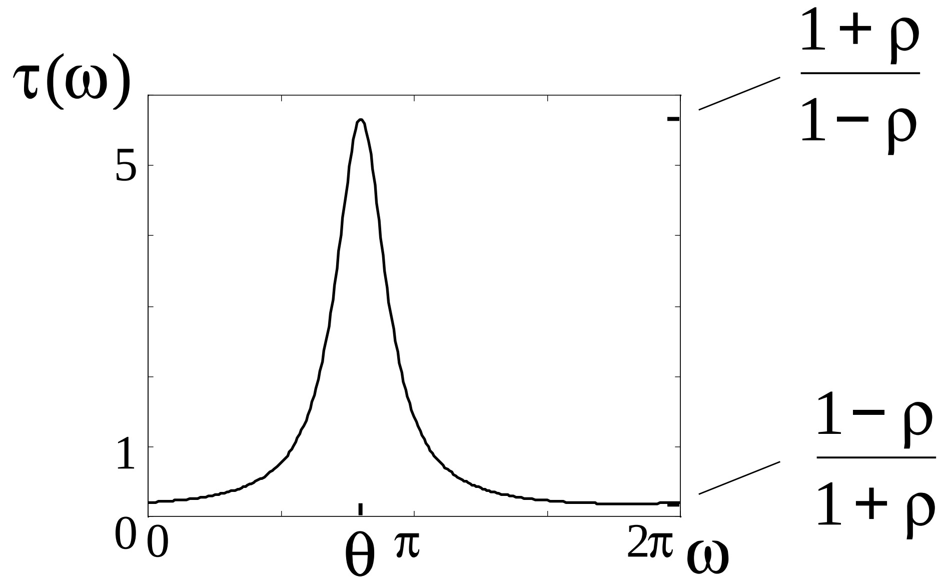
Allpass Dispersion Filter Design

$$G(z) = \frac{\rho_N + \rho_{N-1} z^{-1} + \cdots + \rho_1 z^{-N+1} + z^{-N}}{1 + \rho_1 z^{-1} + \cdots + \rho_{N-1} z^{-N+1} + \rho_N z^{-N}}$$

- **Hilbert transform methods**
  - **Yegnanarayana, IEEE-ASSP 1982**
  - **Reddy and Swamy, ICASSP 1998**
  - **Filter phase (not group delay) matched**
  - **Potential time aliasing, numerical issues; not in factored form**
- **Optimal filter design formulation**
  - **Lang and Laakso, IEEE-CAS1 1994; Lang, IEEE-SP 1998**
  - **Rocchesso and Scalcon, IEEE-CAS 1996**
  - **Bensa et al., ASA 2004**
  - **Rauhala and Valamaki, IEEE-SPL 2006**
  - **Maximum order limited by numerical difficulties; expensive design**

First-Order Allpass Filter





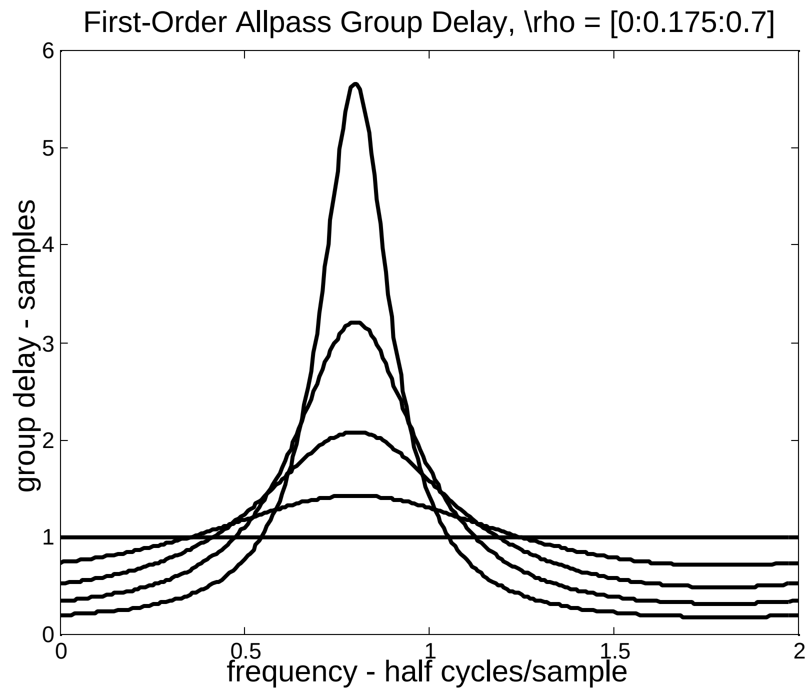
$$G(z) = \frac{-\rho e^{-j\theta} + z^{-1}}{1 - \rho e^{j\theta} \; z^{-1}}$$

$$\tau(\omega) = \frac{1-\rho^2}{1+\rho^2 - 2\rho\cos(\omega-\theta)}$$

transfer function

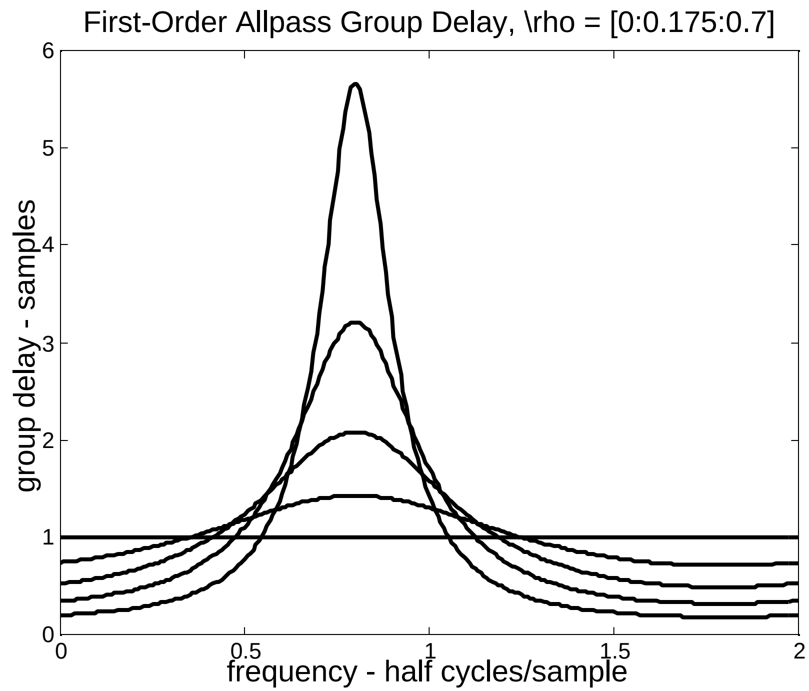
group delay

First-Order Allpass Group Delay



- **As the pole is moved toward the unit circle, the first-order allpass group delay $\tau(\omega)$ becomes more peaked about the pole angle θ – the maximum increases, and the peak narrows.**

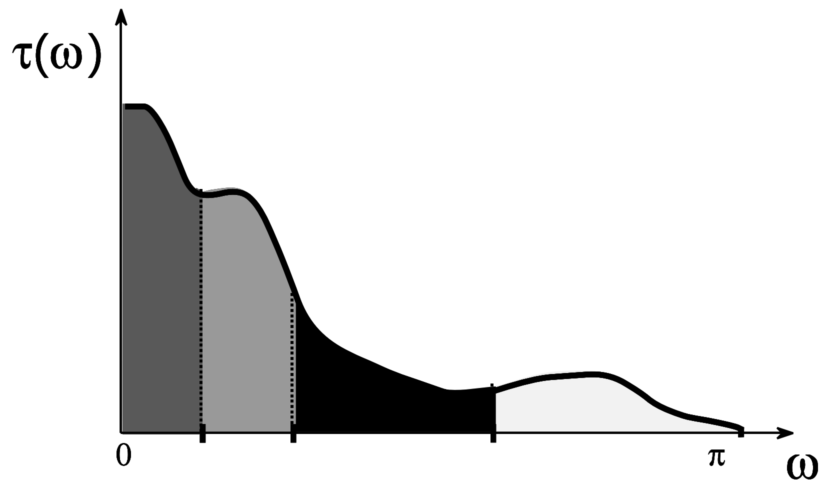
First-Order Allpass Group Delay



- **The integral of the group delay $\tau(\omega)$ of a first-order allpass filter is 2π, independent of ρ and θ,**

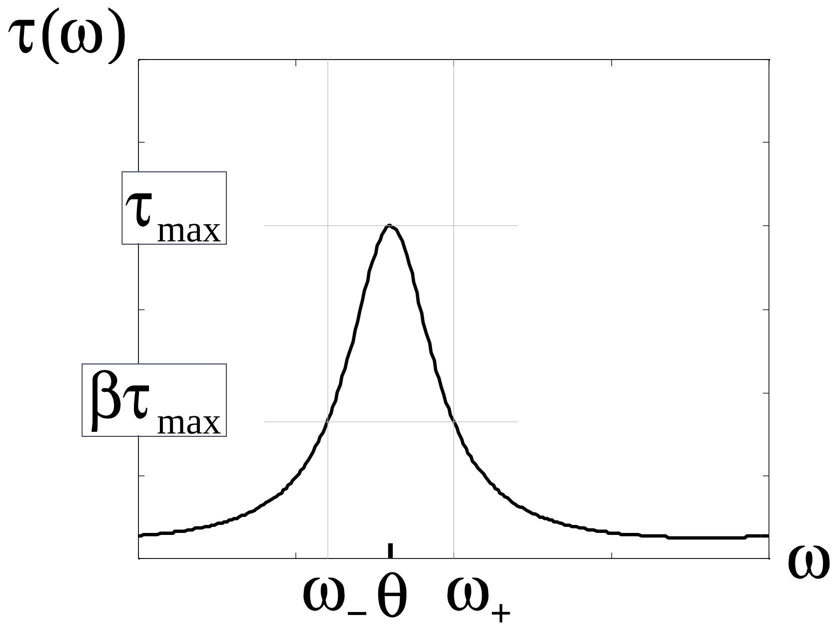
$$\int_0^{2\pi} \tau(\omega)\,d\omega = \varphi(2\pi) - \varphi(0) = 2\pi\,.$$

Allpass Filter Design Approach



- **Integrate $\tau(\omega)$, and add a constant delay τ_0 such that $\tau(\omega)+\tau_0$ integrates to a multiple of 2π.**
- **Divide $\tau(\omega)+\tau_0$ into 2π -area frequency bands.**
- **Fit a first-order allpass filter section to each band.**

First-Order Allpass Design



$$\rho = \eta - \left[\eta^2 - 1\right]^{1/2}$$

$$\eta = \frac{1 - \beta\cos\delta}{1 - \beta}$$

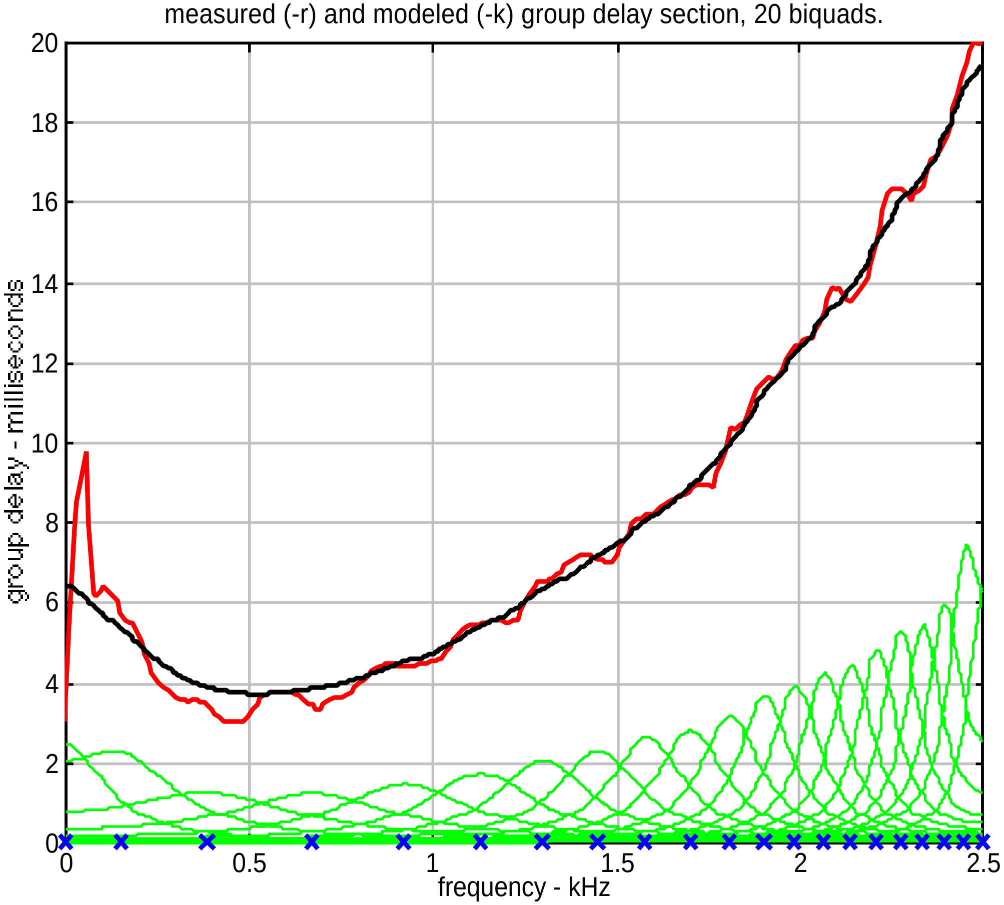
$$\delta = (\omega_- - \omega_+)/2$$

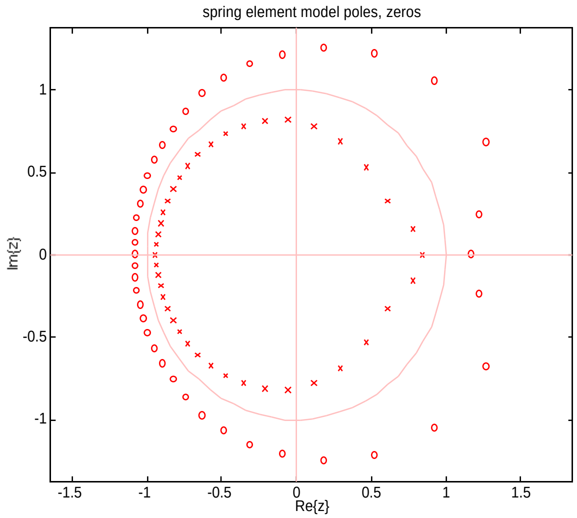
- **The pole angle θ is the band midpoint,**

$$\theta = (\omega_- + \omega_+)/2$$

- **The section pole radius ρ is chosen to make the band edge group delay a fraction β of its maximum.**

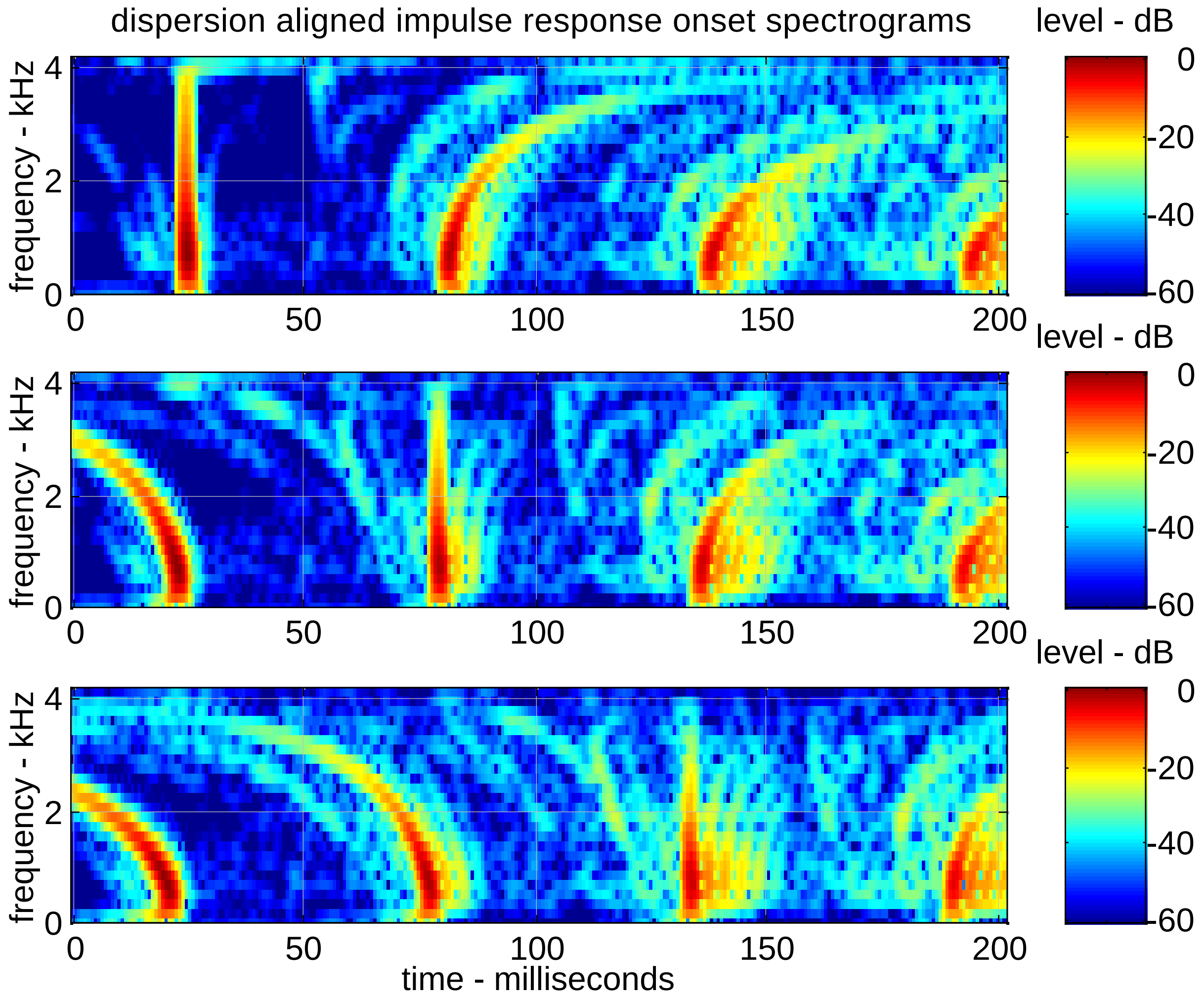
Dispersion Filter Model



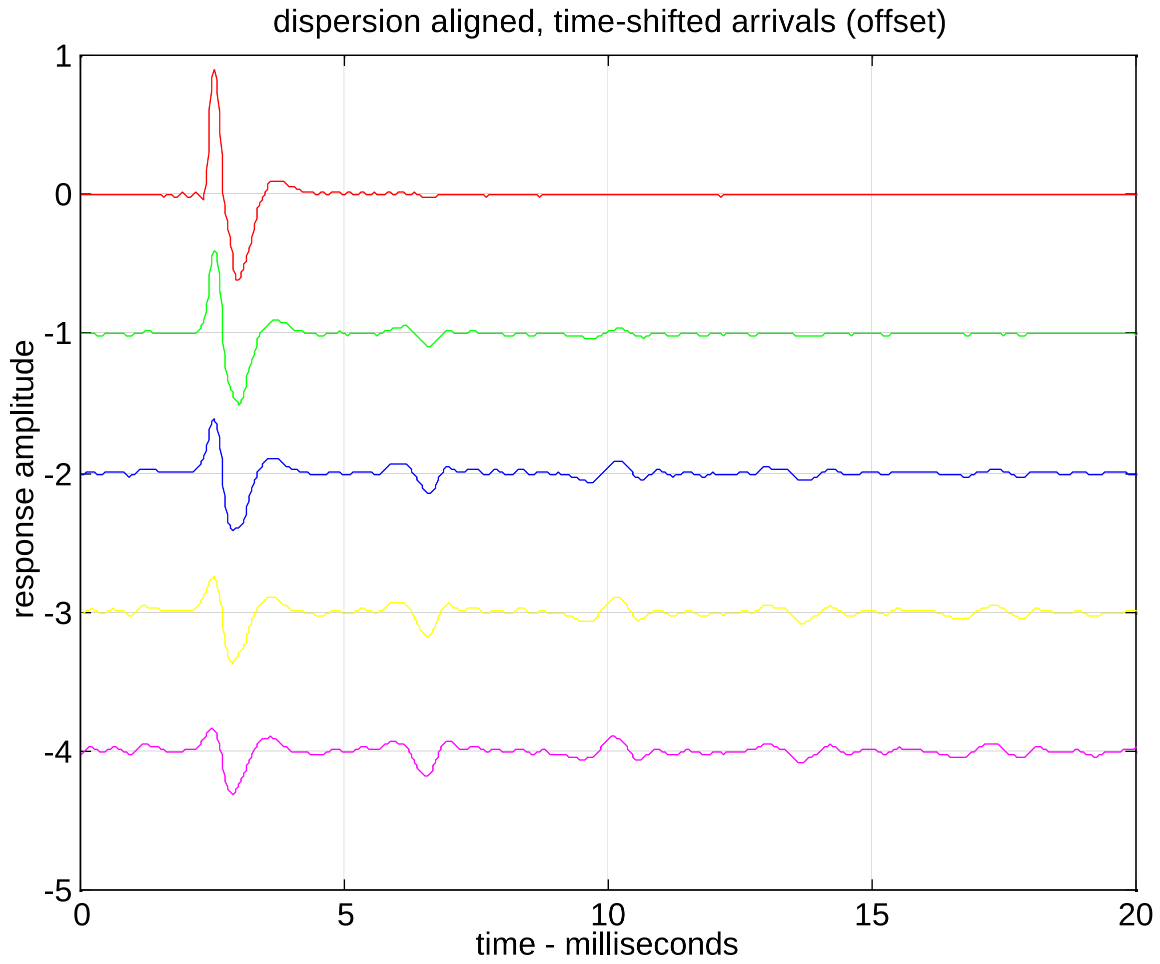


- **The dispersion filter is chosen to match the allpass component of the spring traversal group delay.**

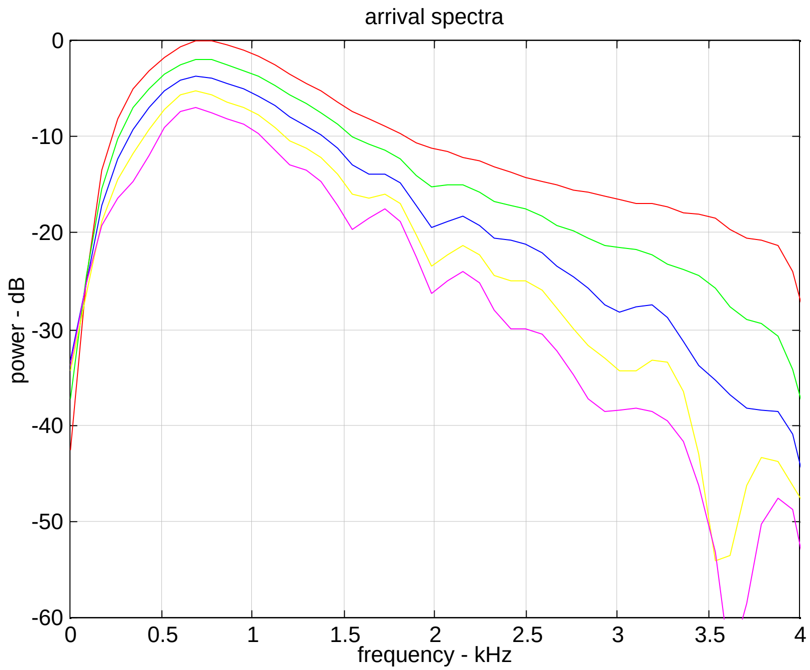
Dispersion Aligned Arrivals

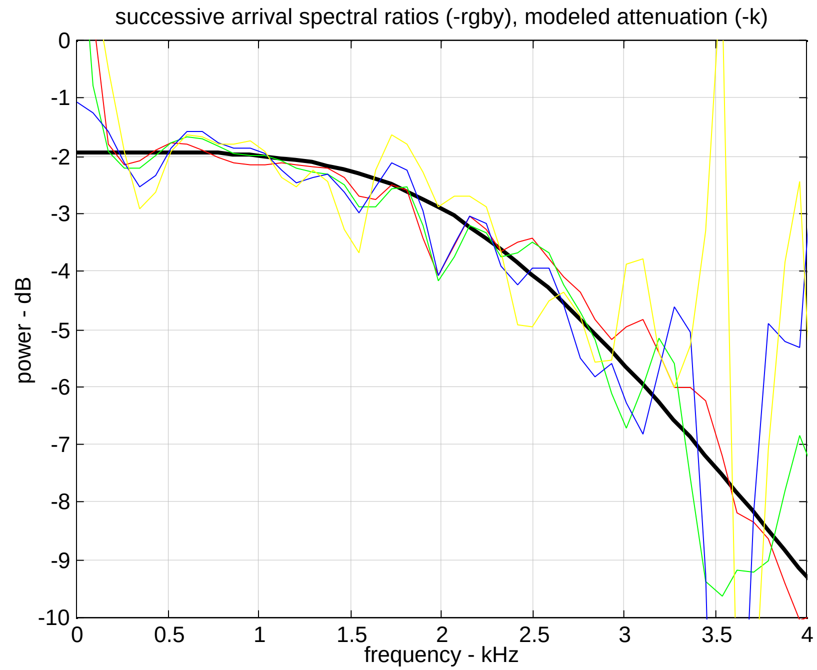


Dispersion Aligned Arrivals



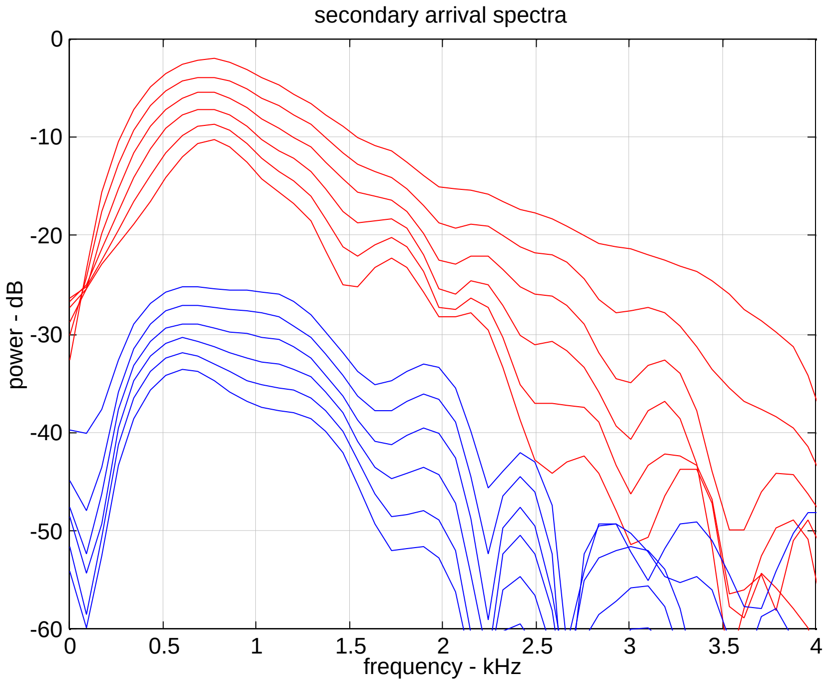
Attenuation Filter Model

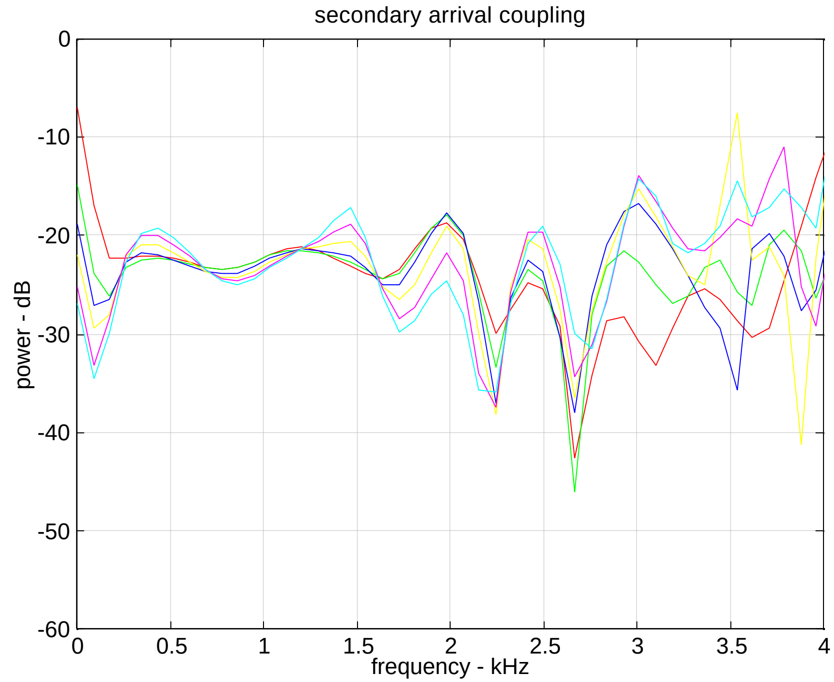


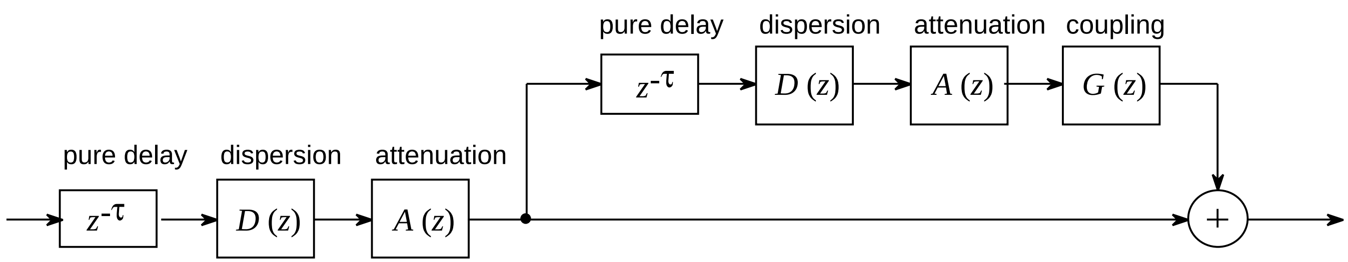


- **The attenuation filter is modeled after the ratio of successive arrival transfer functions.**

Secondary Arrival Model

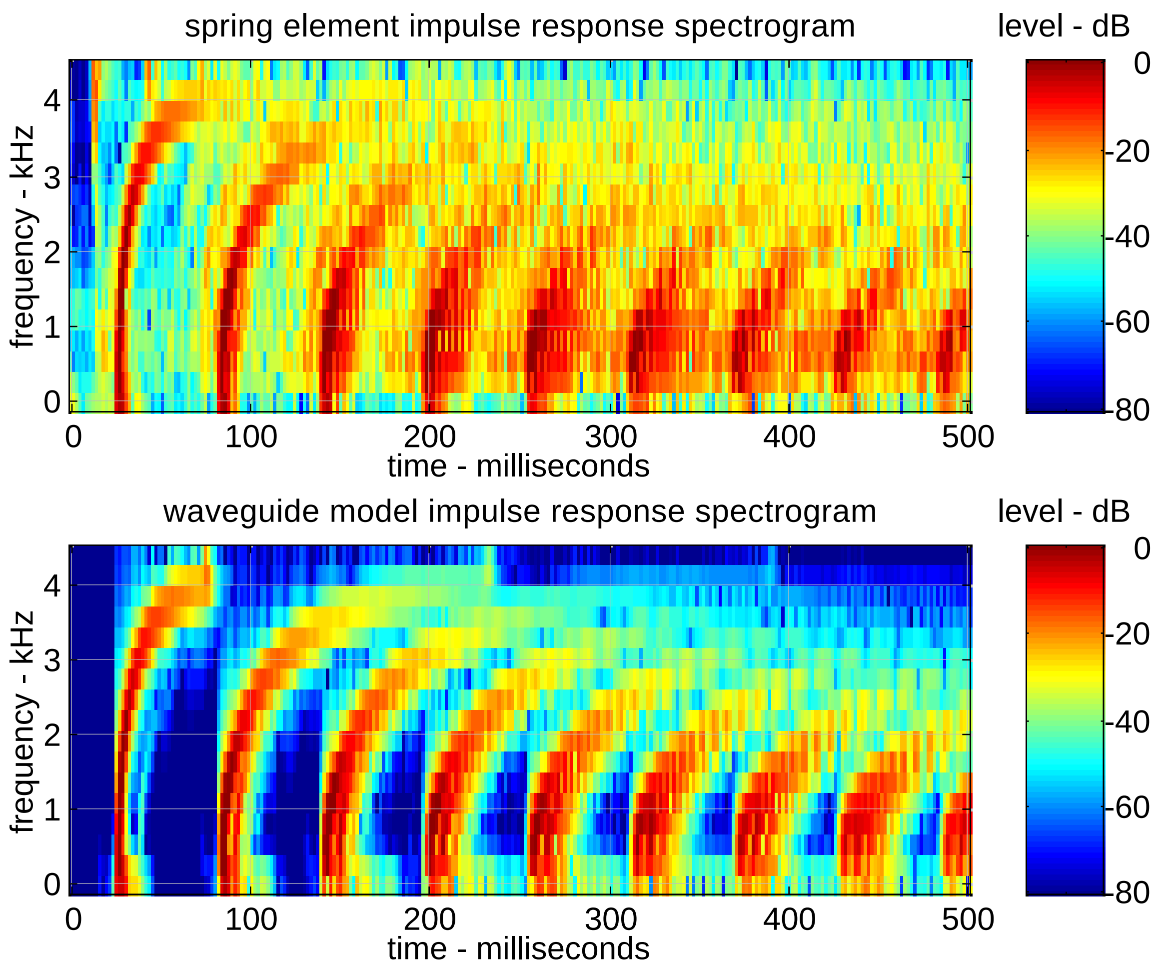


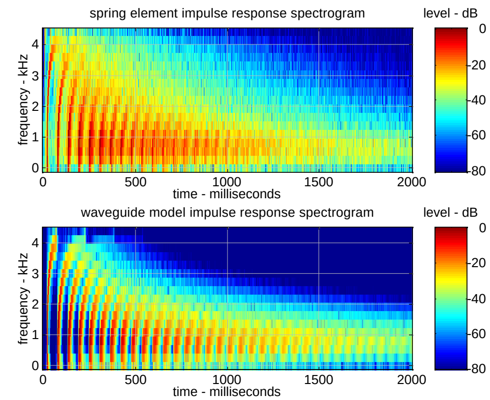




- **Secondary arrivals are consistent with a coupling between the longitudinal and torsional modes.**

Measured and Modeled Spring Spectrograms





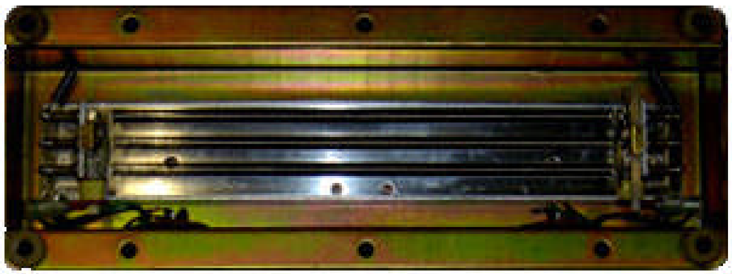
dry

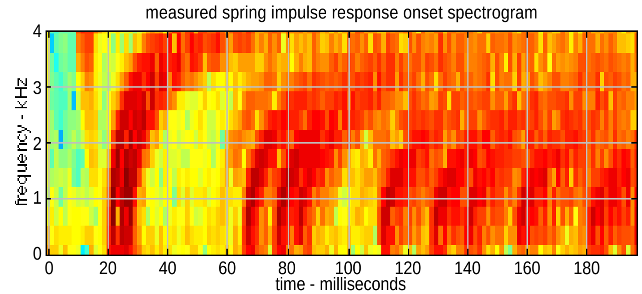
measured

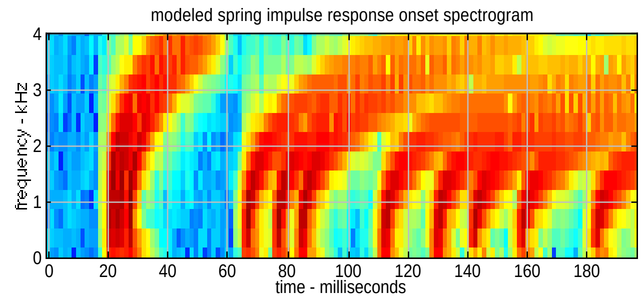
modeled

Spring Model Summary

dry

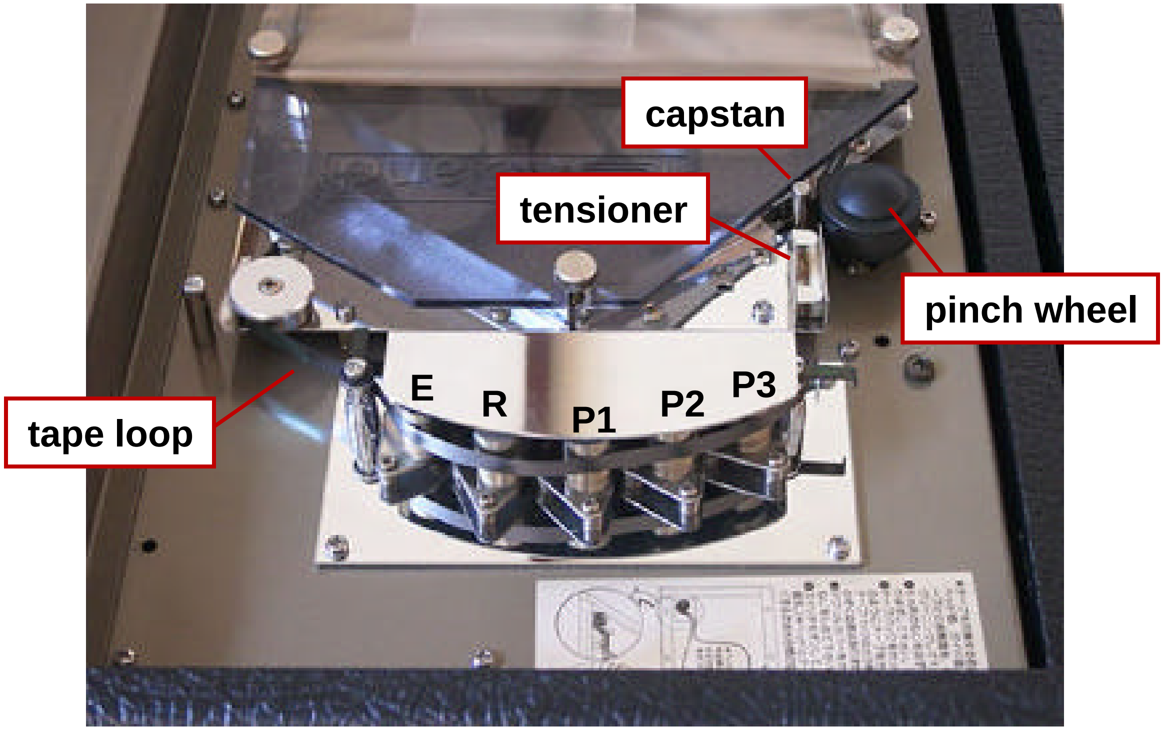


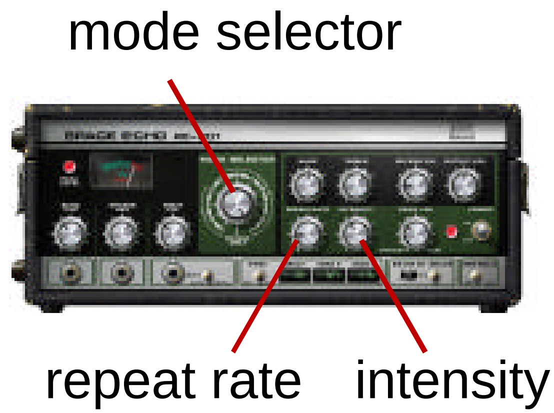


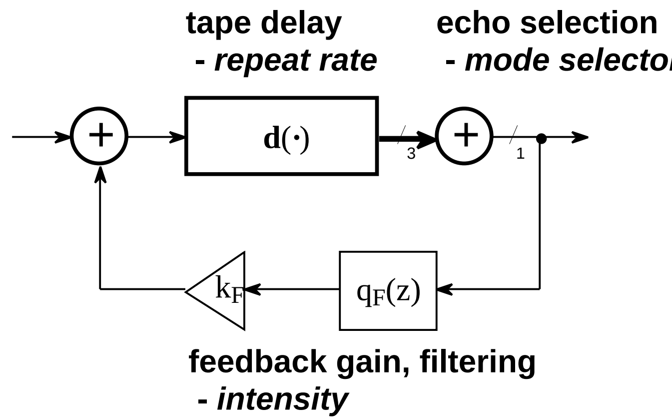


- **Spring propagation**
  - **Strongly dispersive; cutoff frequency**
  - **Coupled torsional, longitudinal modes**
- **Spring reverberator emulation**
  - **Efficient dispersive waveguide structure**
  - **Model elements fit to impulse response measurements from the unit being emulated**

Tape Echo

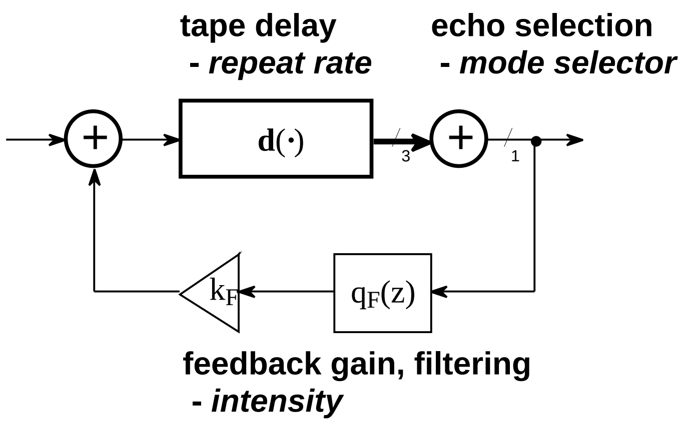


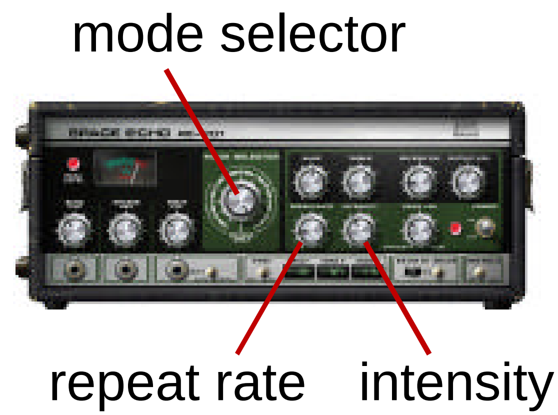


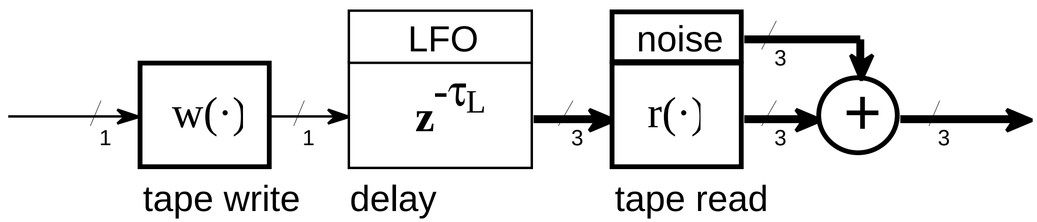


- **Multiple play heads read the input signal, delayed according to the tape speed and head spacing.**
- **The tape transport produces a fluctuating delay time responsible for much of the tape echo sonics.**

Tape Echo Model

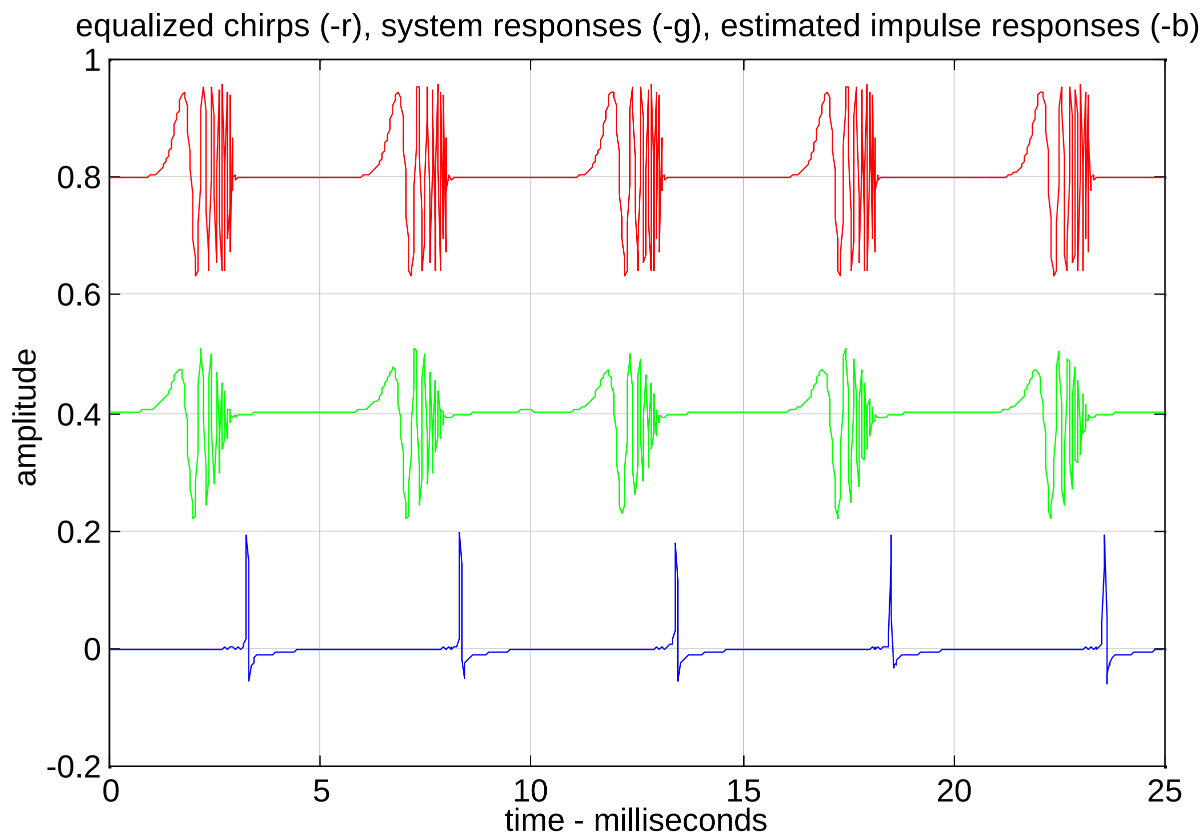


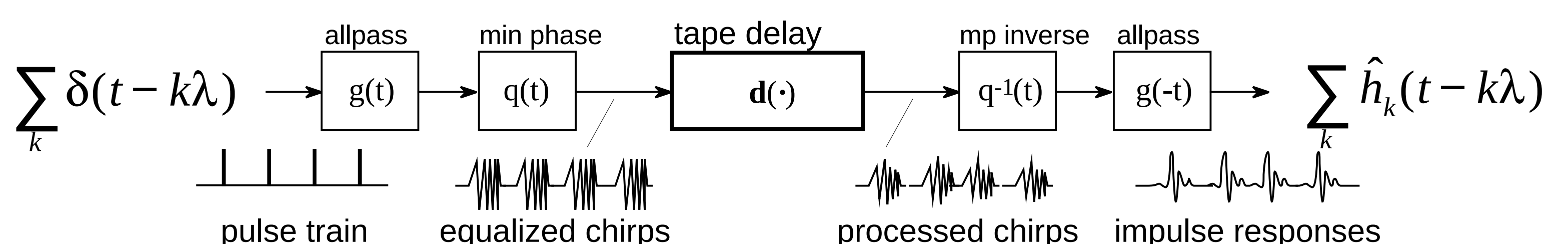




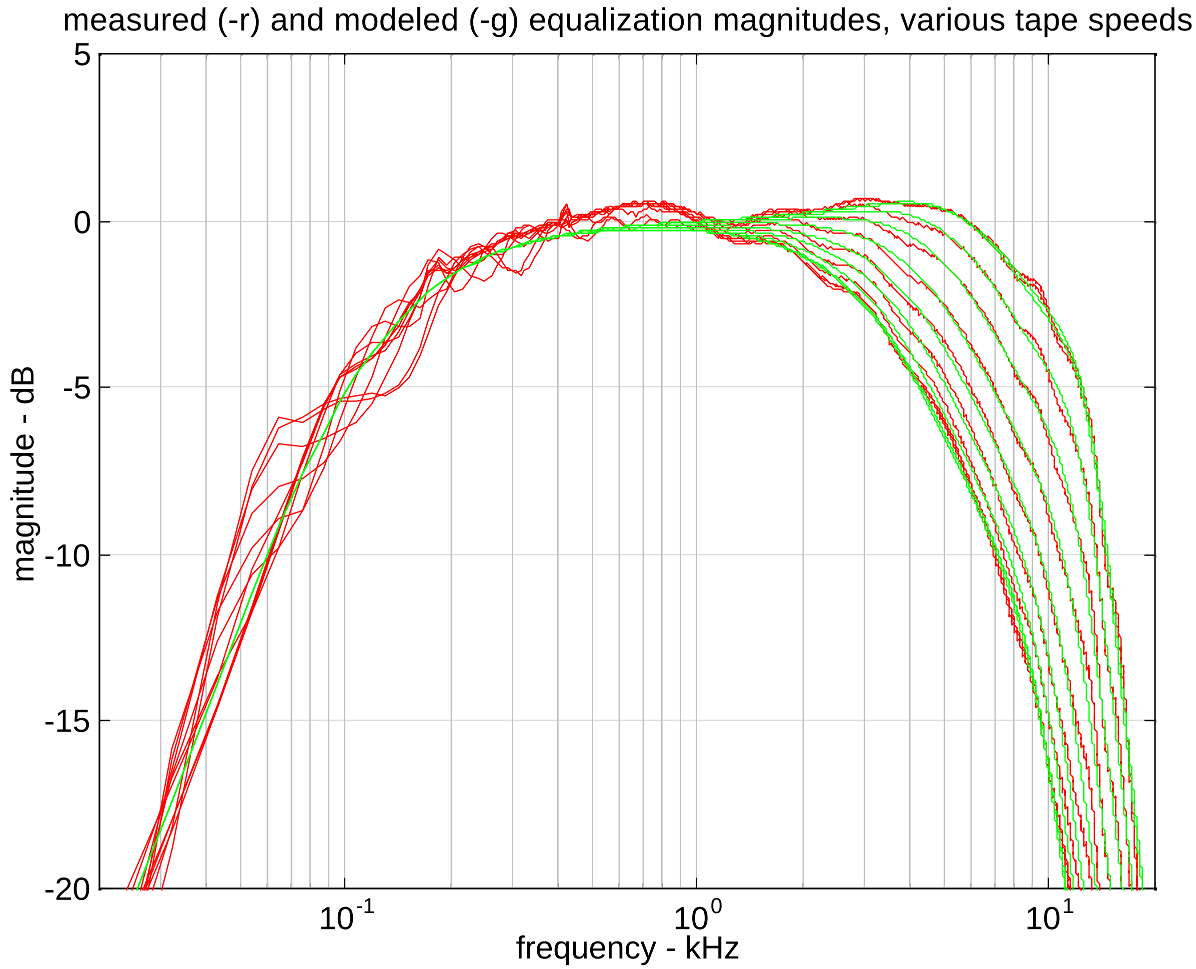
- **The tape delay is simulated using separate record and playback processes, driven by a fluctuating tape speed.**

Time Delay, Transfer Function Measurement

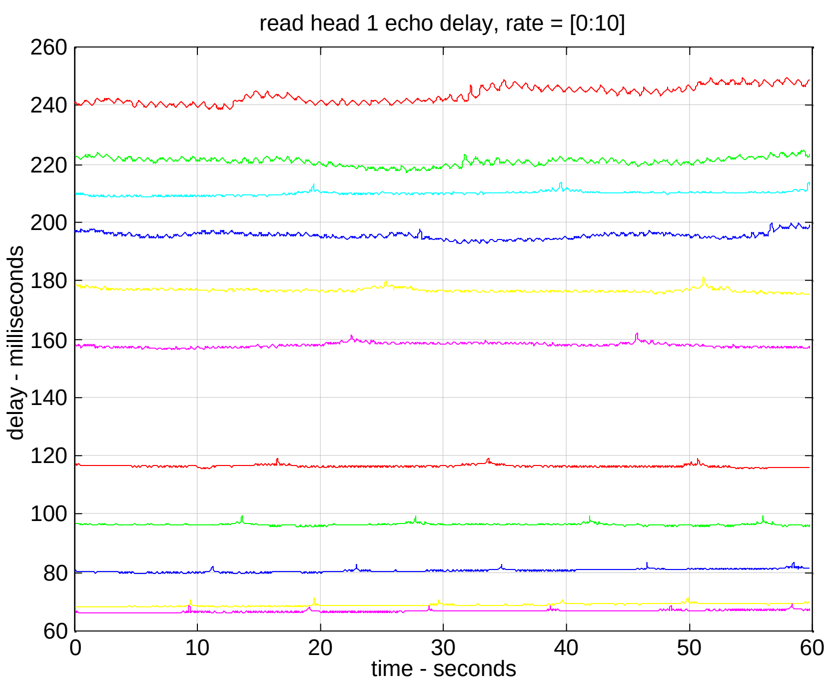


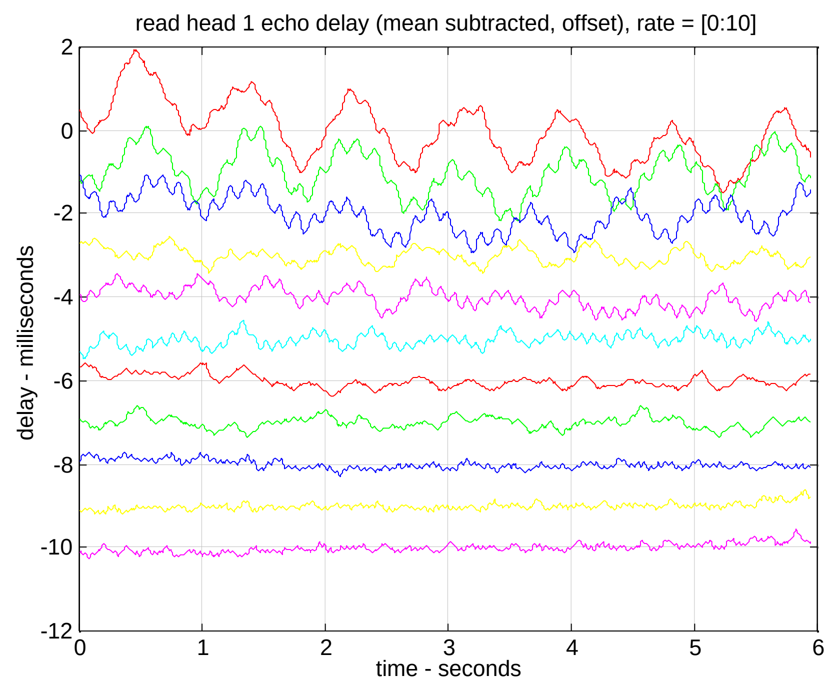


Tape Speed-Dependent Equalization



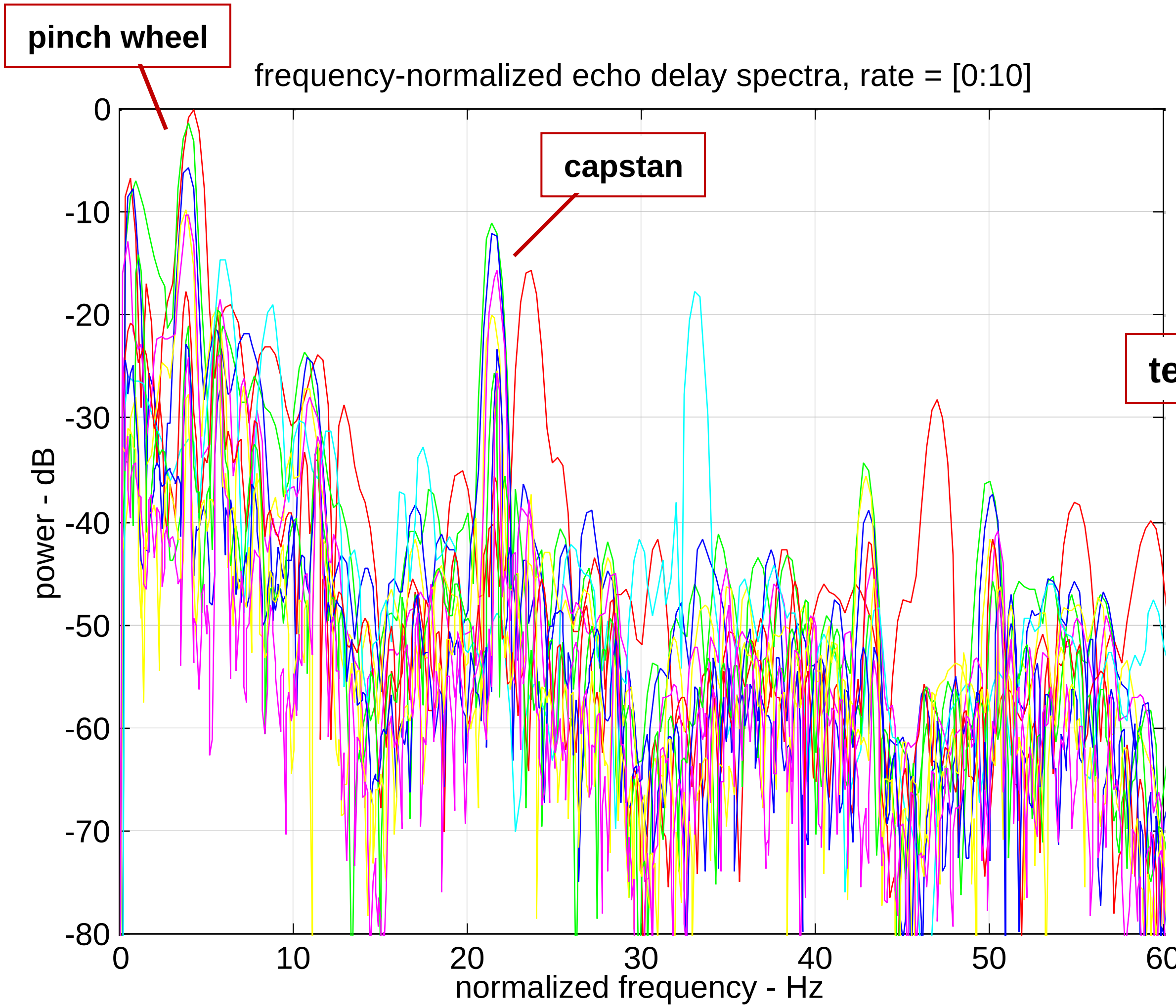
Delay Trajectories, Static Rates

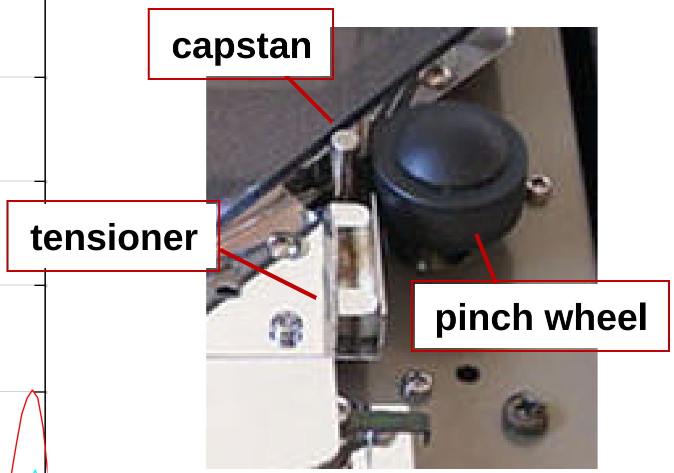




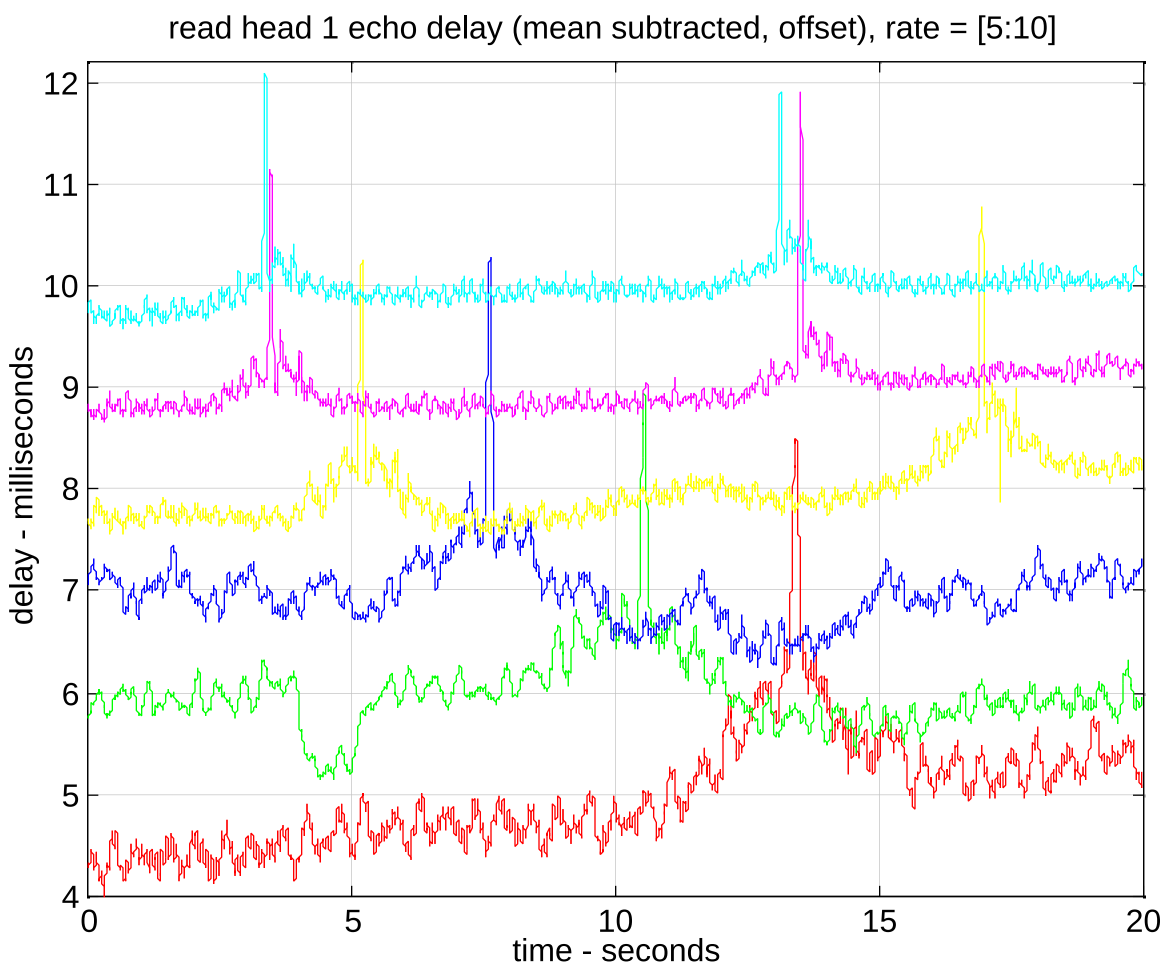
- **The tape transport produces a time varying delay with quasi-periodic and noise-like components.**

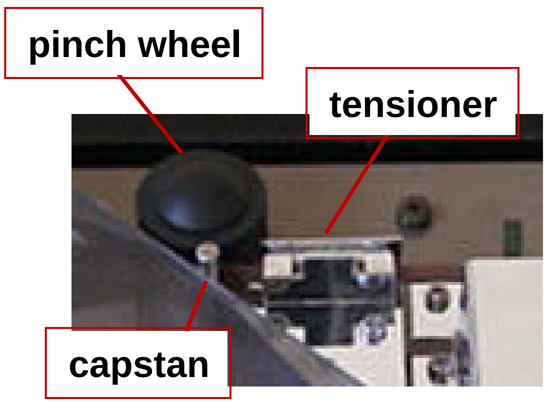
Delay Trajectory Spectra, Static Rates



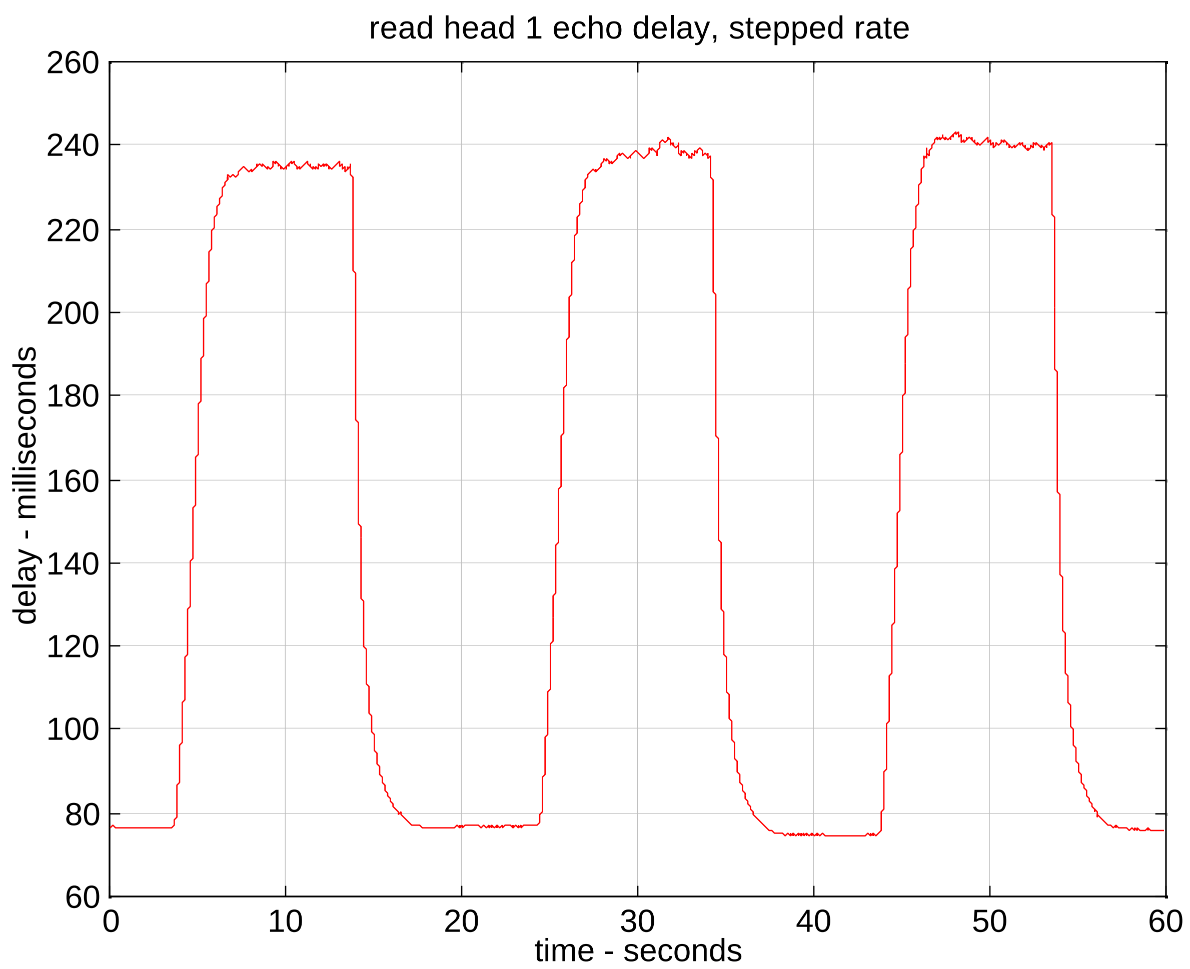


Delay Trajectories, Splice Detail

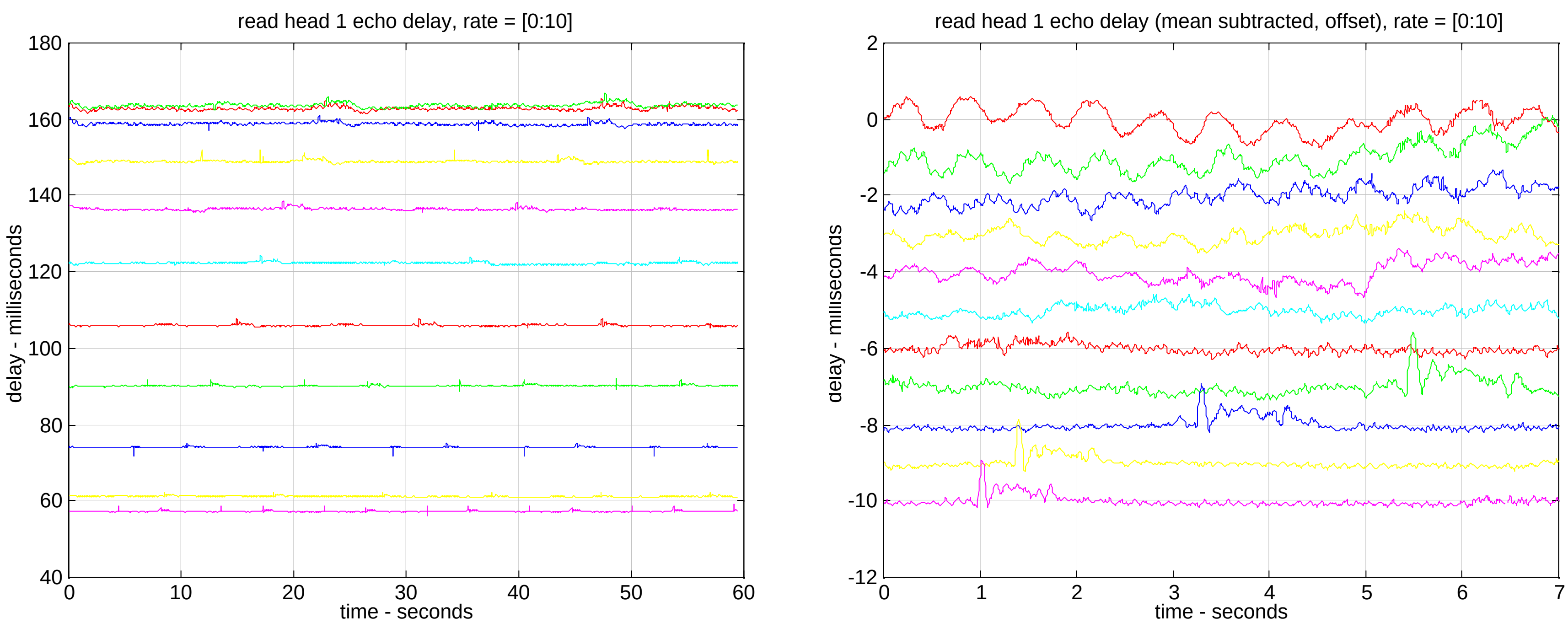




Delay Trajectories, Stepped Rate Control

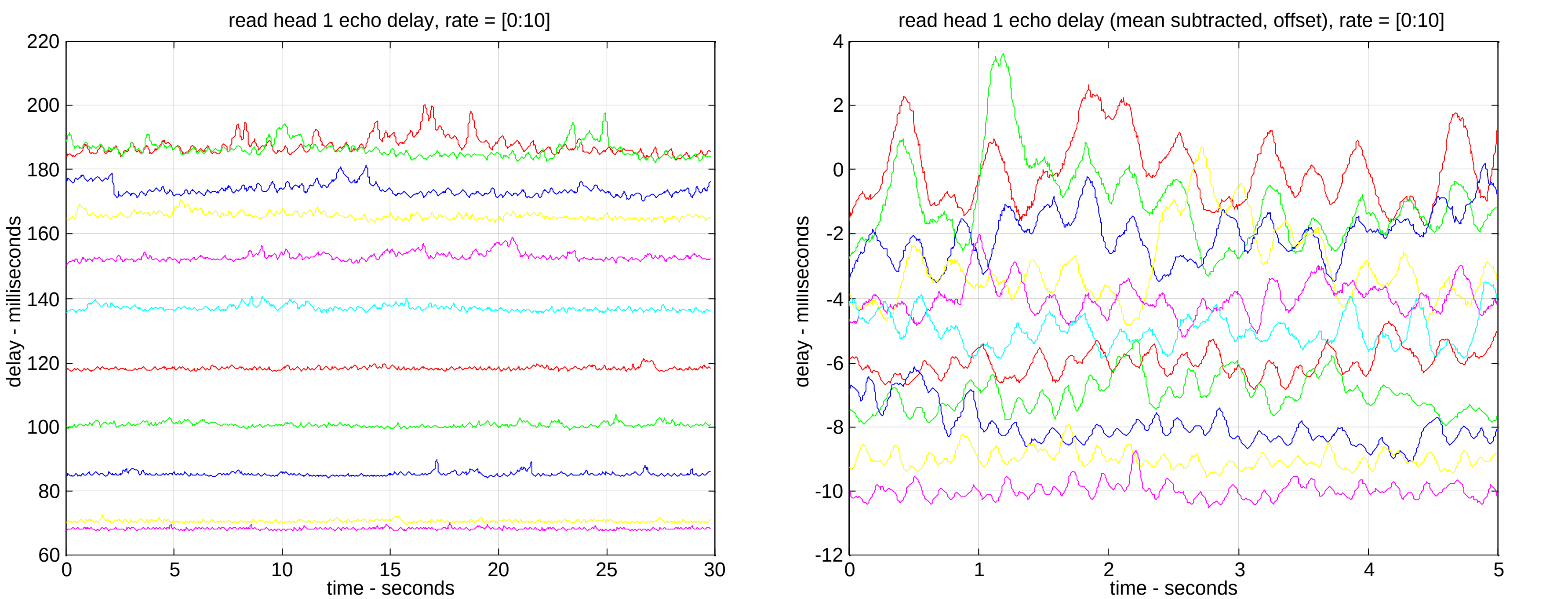


Delay Trajectories, Static Rate Control



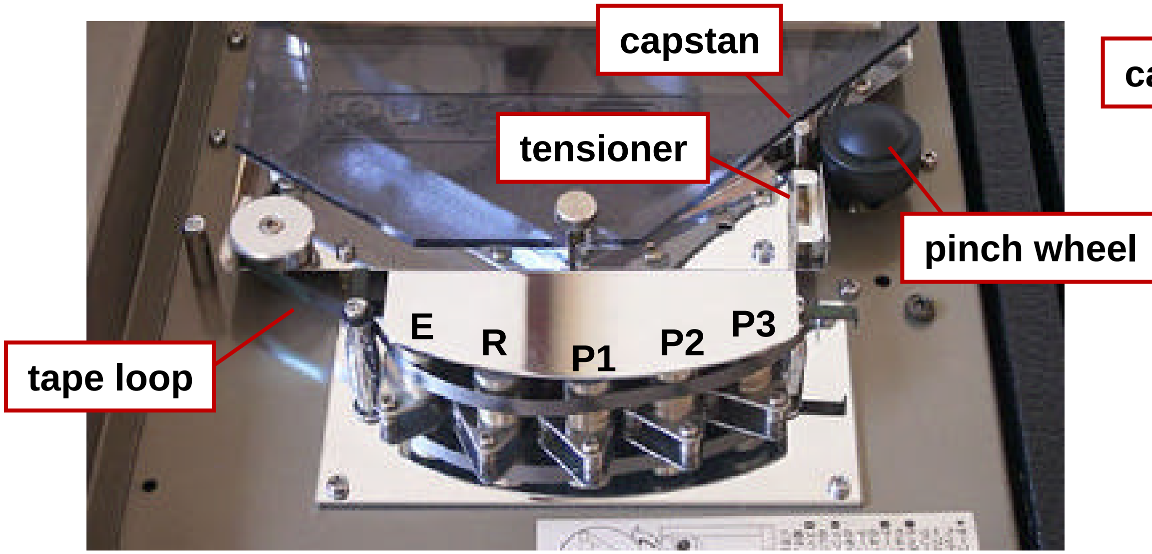
- **The character of the delay trajectory depends on factors such as tape age.**

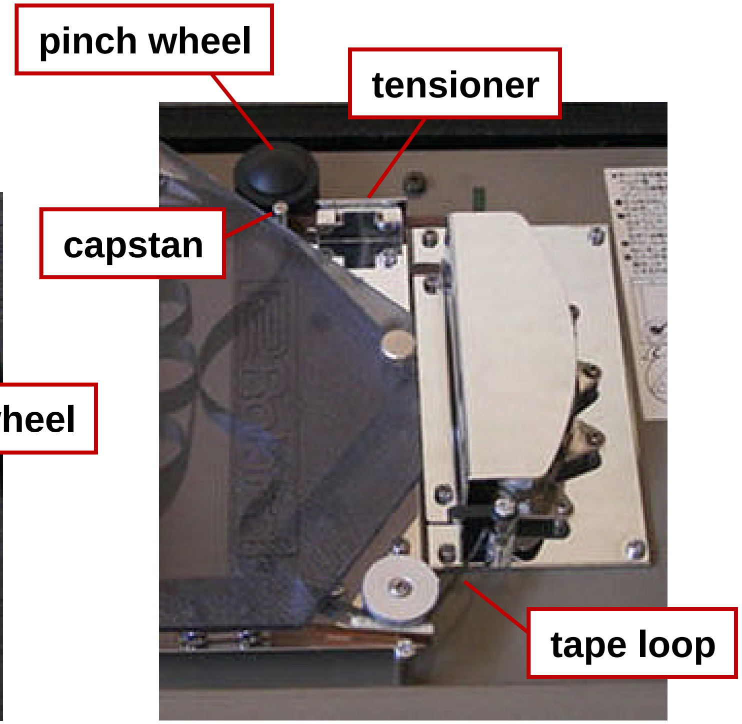
Delay Trajectories, Static Rate Control



- **The character of the delay trajectory depends on factors such as tape age.**

Tape Transport Model



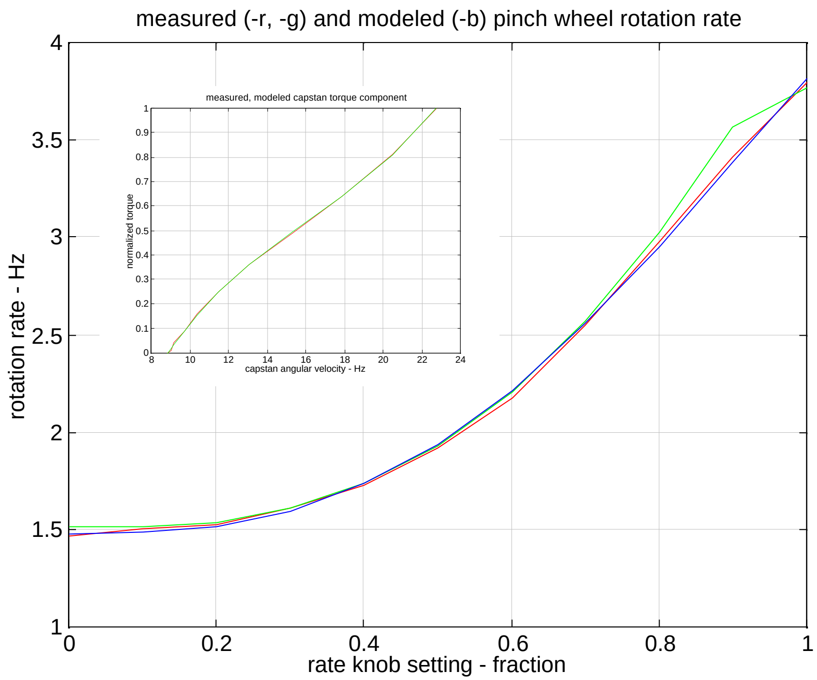


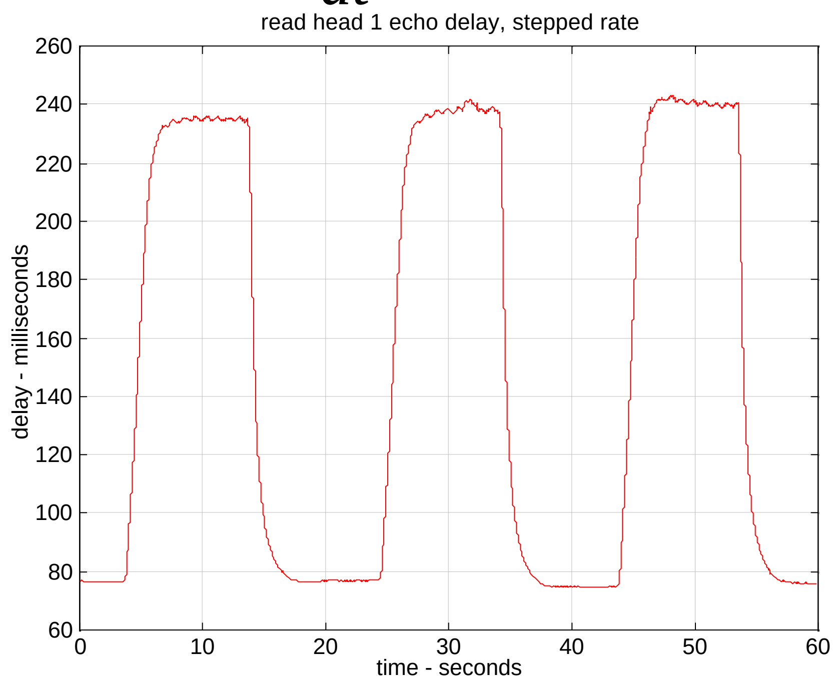
$$\underset{\text{fly wheel moment}}{I}\,\frac{\overset{\text{capstan angular velocity}}{d\omega_c}}{dt} = \underbrace{\tau(r,\omega_c)}_{\text{motor torque}} - \underbrace{\mu\ \overset{\text{tape tension}}{T(v)}\ \overset{\text{capstan radius}}{\rho_c}(\theta_c)}_{\text{tensioner friction}} - \underbrace{\gamma(\overset{\text{pinch wheel radius}}{\rho_p}(\theta_p))}_{\text{pinch wheel deformation}}$$

Steady-State, Dynamic Motor Torque

$$\tau(r,\omega_c) = \eta\left[\varphi(r) - \psi(\omega_c)\right] = 0$$

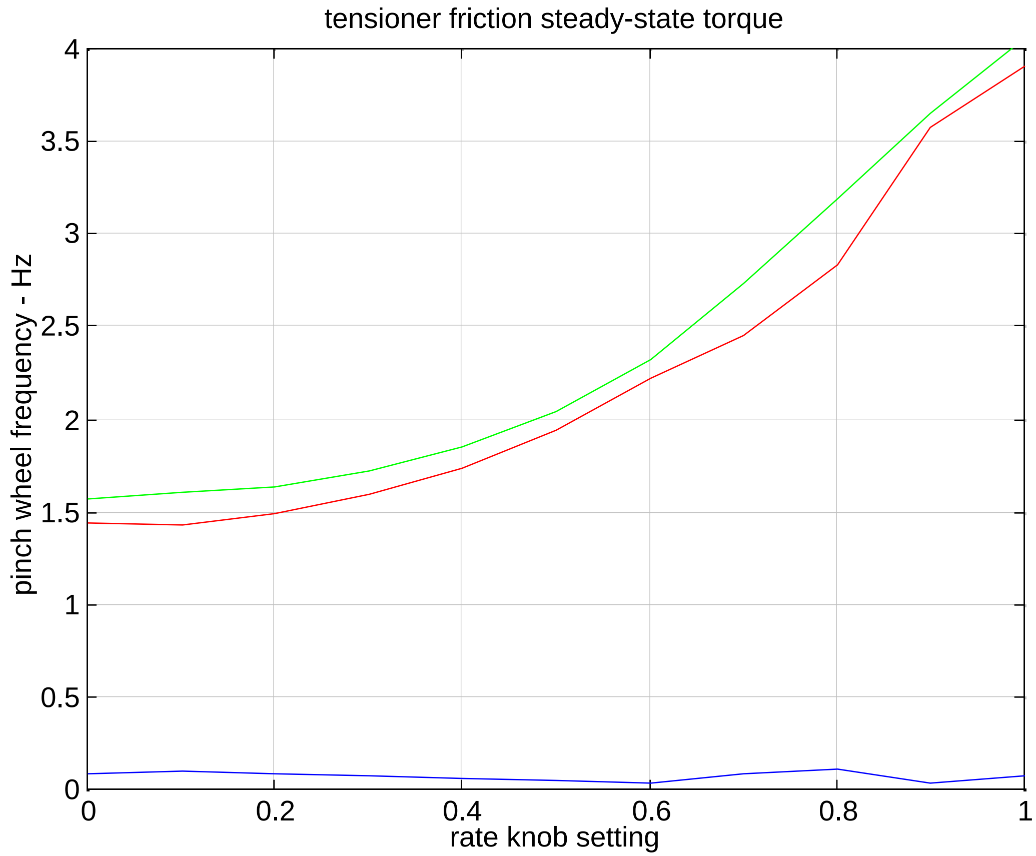
$$I\,\frac{d\omega_c}{dt} = \tau(r,\omega_c)$$





$$\tau(r,\omega_c) = \begin{cases} \eta_A\left[\varphi(r) - \psi(\omega_c)\right], & \varphi(r) \geq \psi(\omega_c) \\ \eta_R\left[\varphi(r) - \psi(\omega_c)\right], & \varphi(r) < \psi(\omega_c) \end{cases}$$

Tensioner-Tape Friction Steady-State Torque



$$\frac{d\omega_c}{dt} = 0 \quad \rightarrow \quad \mu \;\; T(v) = \eta\left[\varphi(r) - \psi(\omega_c)\right] / \rho_c$$

Pinch Wheel Deformation

- **Deformation energy stored, kinetic energy acquired in time Δt,**

$$E_s = \tfrac{1}{2} k \ \rho_p^2(\theta_p) \quad \rightarrow \quad \Delta E_s = \tfrac{1}{2} k \ \rho_p(\theta_p) \ \frac{d\rho_p}{d\theta_p} \frac{d\theta_p}{dt} \Delta t$$

$$E_\omega = \tfrac{1}{2} I \ \omega_c^2 \quad \rightarrow \quad \Delta E_\omega = I \ \omega_c \ \frac{d\omega_c}{dt} \Delta t$$

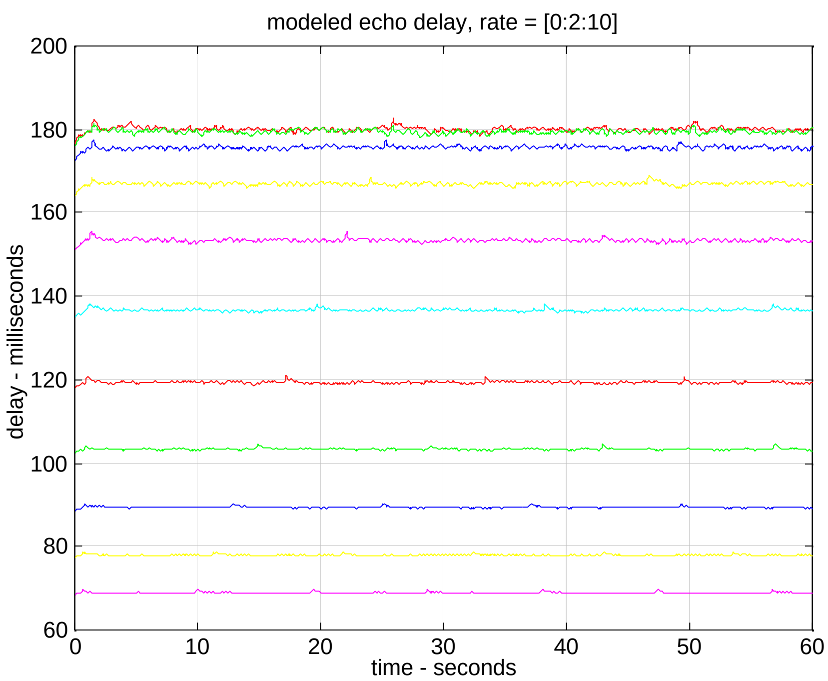
- **Pinch wheel deformation torque, $\Delta E_s + \Delta E_\omega = 0$:**

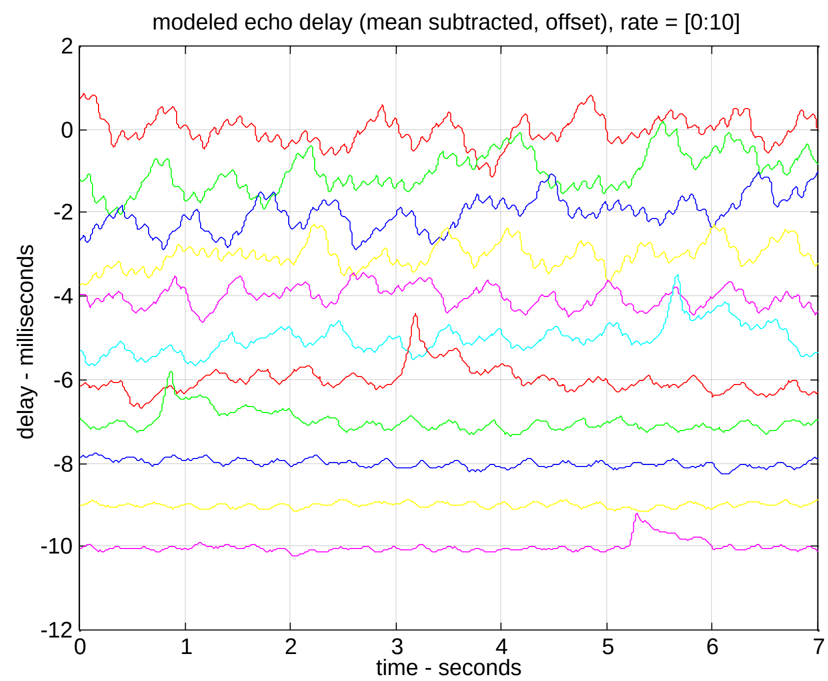
$$\gamma(\rho_p(\theta_p)) = I \frac{d\omega_c}{dt} = -k \ \frac{\omega_p}{\omega_c} \ \rho_p(\theta_p) \ \frac{d\rho_p}{d\theta_p}$$

- **Off-center pinch wheel radius,**

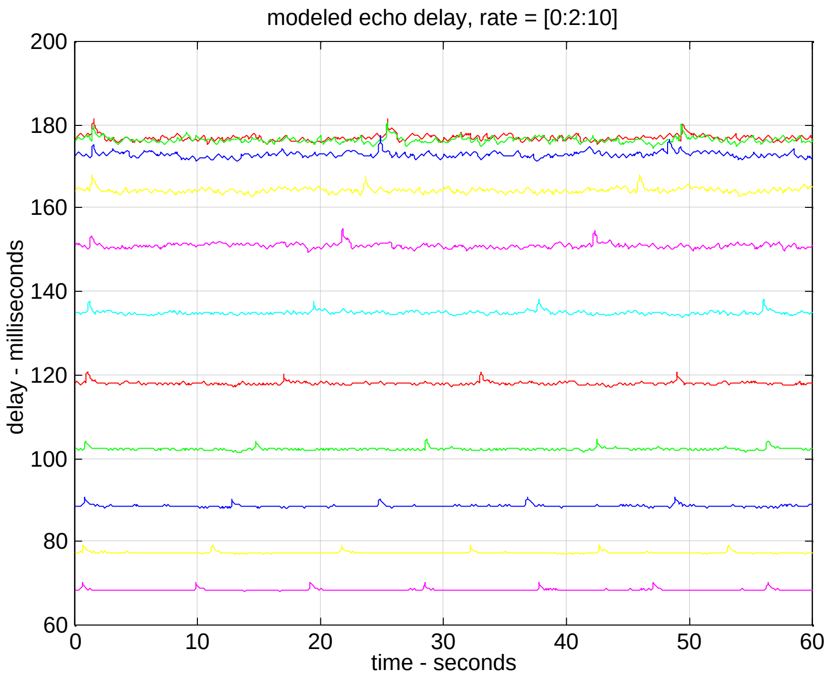
$$\rho_p(\theta_p) = \rho_0 \left[(\cos\theta_p - \beta)^2 + \sin^2\theta_p \right]^{\frac{1}{2}}, \quad \frac{d\rho_p}{d\theta_p} = \frac{\rho_0 \, \beta \sin\theta_p}{\left[(\cos\theta_p - \beta)^2 + \sin^2\theta_p \right]^{\frac{1}{2}}}$$

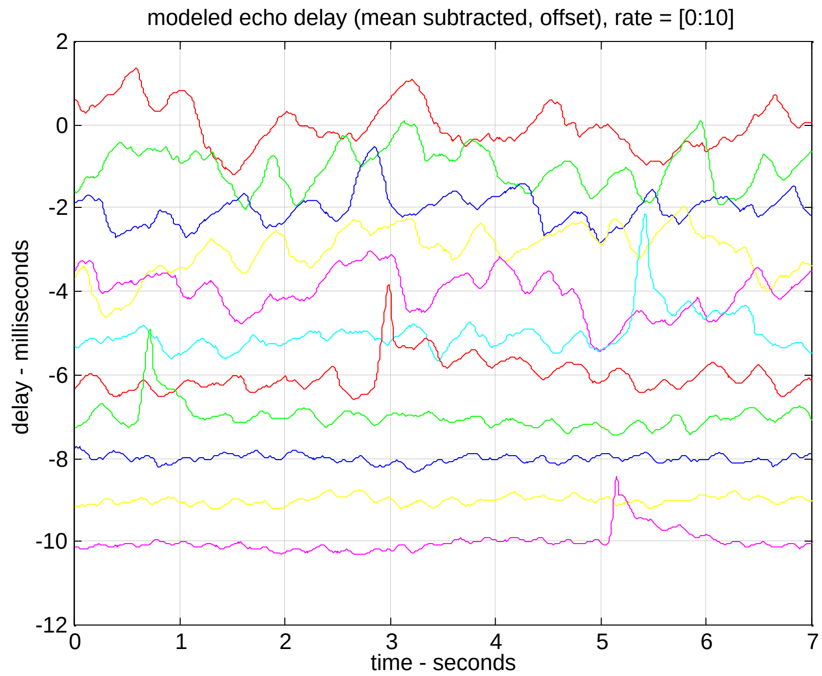
Synthesized Delay Trajectories



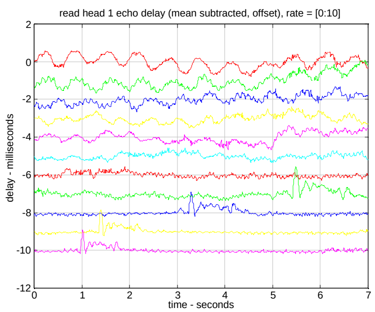


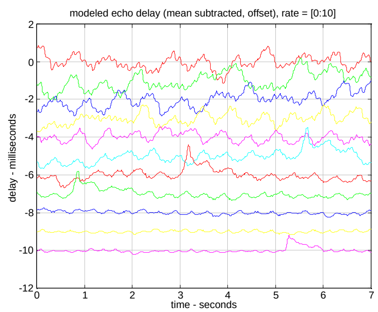
Synthesized Delay Trajectories

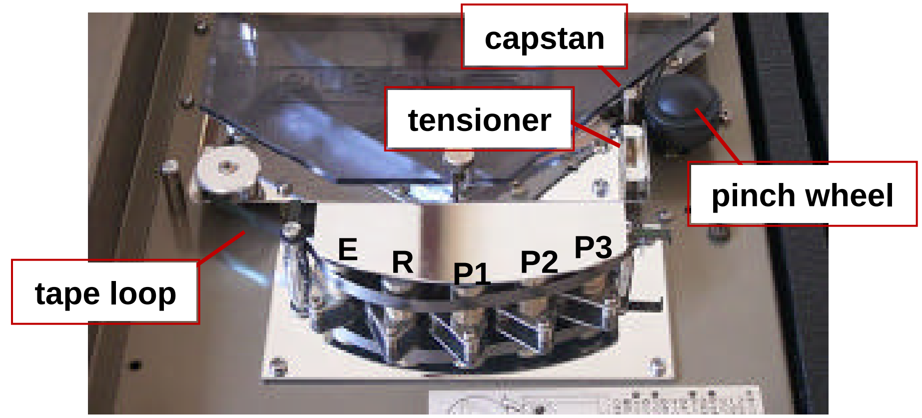




Summary







- **Spring Reverberator Modeling**
  - **Dispersive Waveguide Model**
- **Tape Delay Emulation**
  - **Tape Transport Dynamics Model**
- **Applications / Future Work**
  - **Spring Tanks: Accutronics, AKG**
  - **Tape Echo Units: Echoplex**