A Nonlinear Model for Kemp Echoes

by

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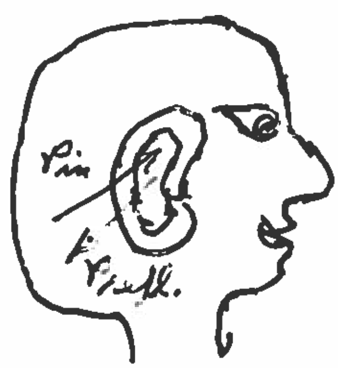
Table of Contents

Motivation

Kemp Echoes appear promising as a diagnostic aid for non-invasive measurements to characterize damage to the inner ear. Therefore it seems worthwhile obtaining more accurate models to give better digital synthesis filters. One property so far ignored is that of nonlinearity

The Kemp Echo

In 1978 D. Kemp* measured evoked acoustic emissions from the ear. These have since been measured by others and are under investigation for noninvasive meaurements to characterize the inner ear.



* D. T. Kemp, "Stimulated Acoustic Emissions from within the Human Auditory System," The Journal of the Acoustical Society of America, Vol. 64, No. 5, November 1978, pp. 1386-1391.

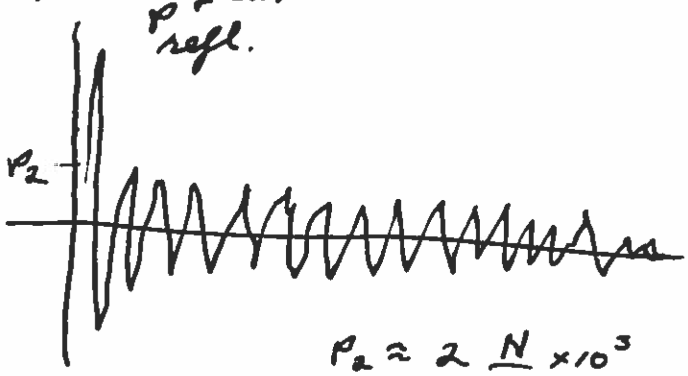
Excitation

$t_1 = 200 \mu s$

$t_p = \frac{1}{16} s$

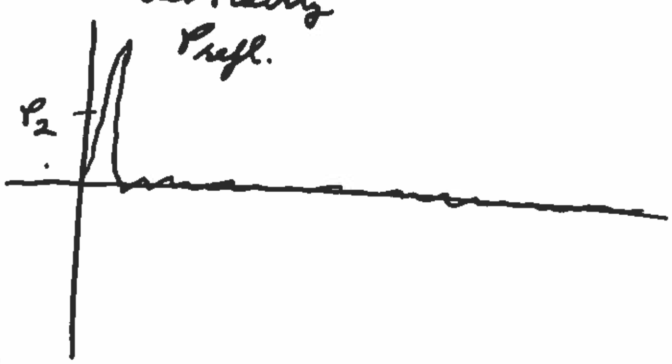
$P_1 = 40 \frac{N}{m^2} \times 10^3$

Healthy Ear

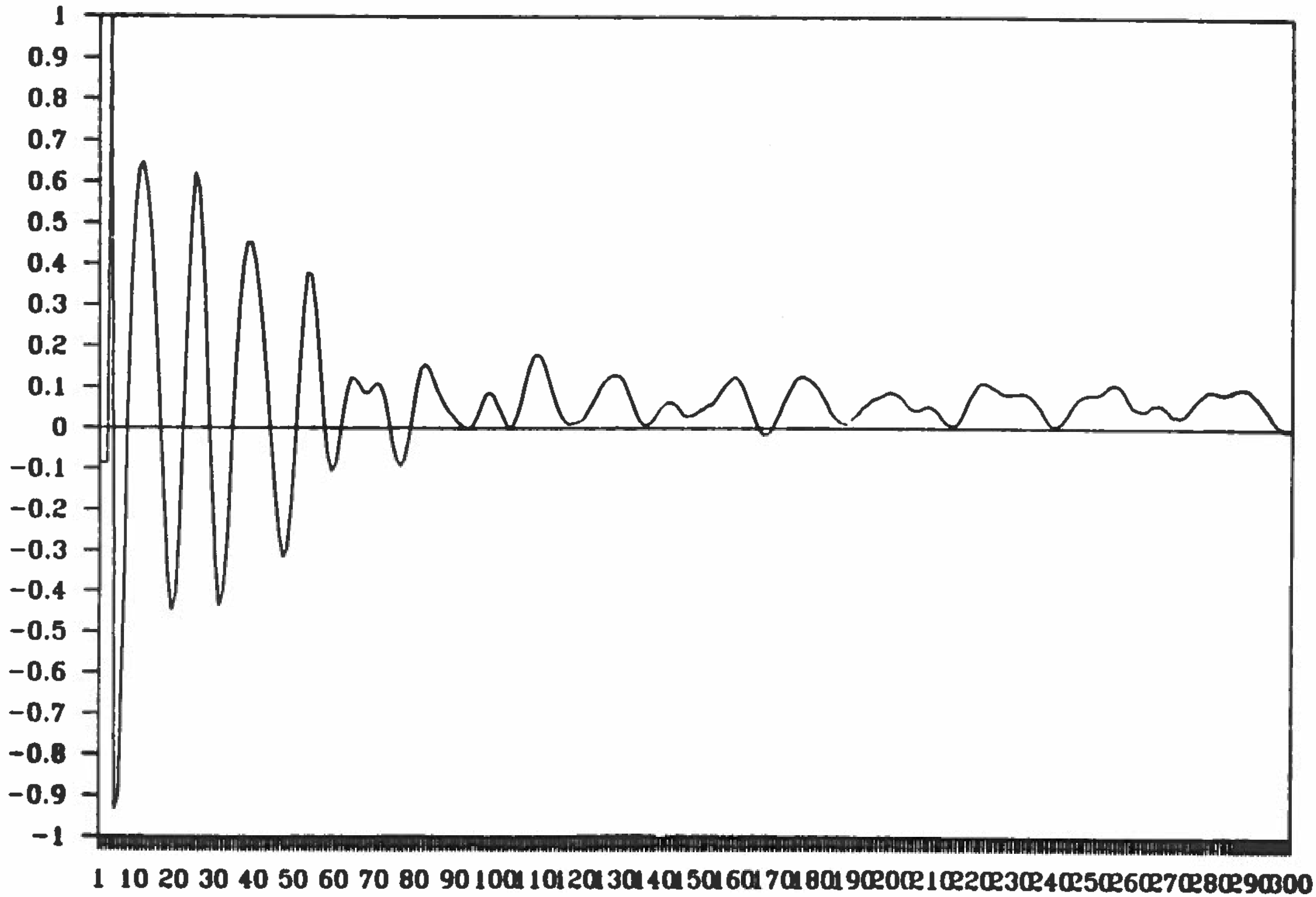


$P_2 \approx 2 \frac{N}{m^2} \times 10^3$

Test Cavity

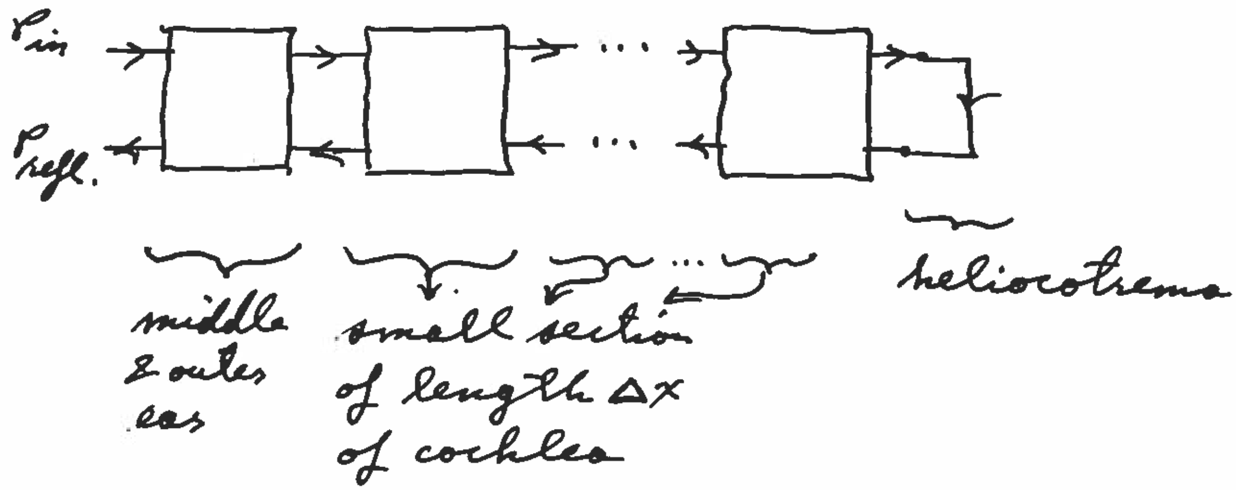


KEMPECHO OUTPUT



Linear Synthesis Filter

Cascade of sections

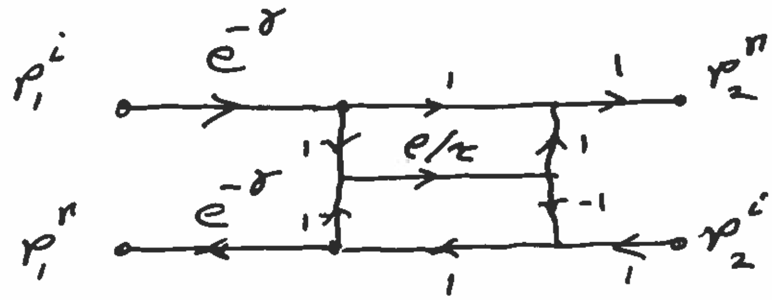


Reduce incident and reflected pressures to one of each by using pressure difference across Basilar membrane

Linear Synthesis Filter – cont.

Middle & outer ear $\approx$ transformer

Cochlea sections

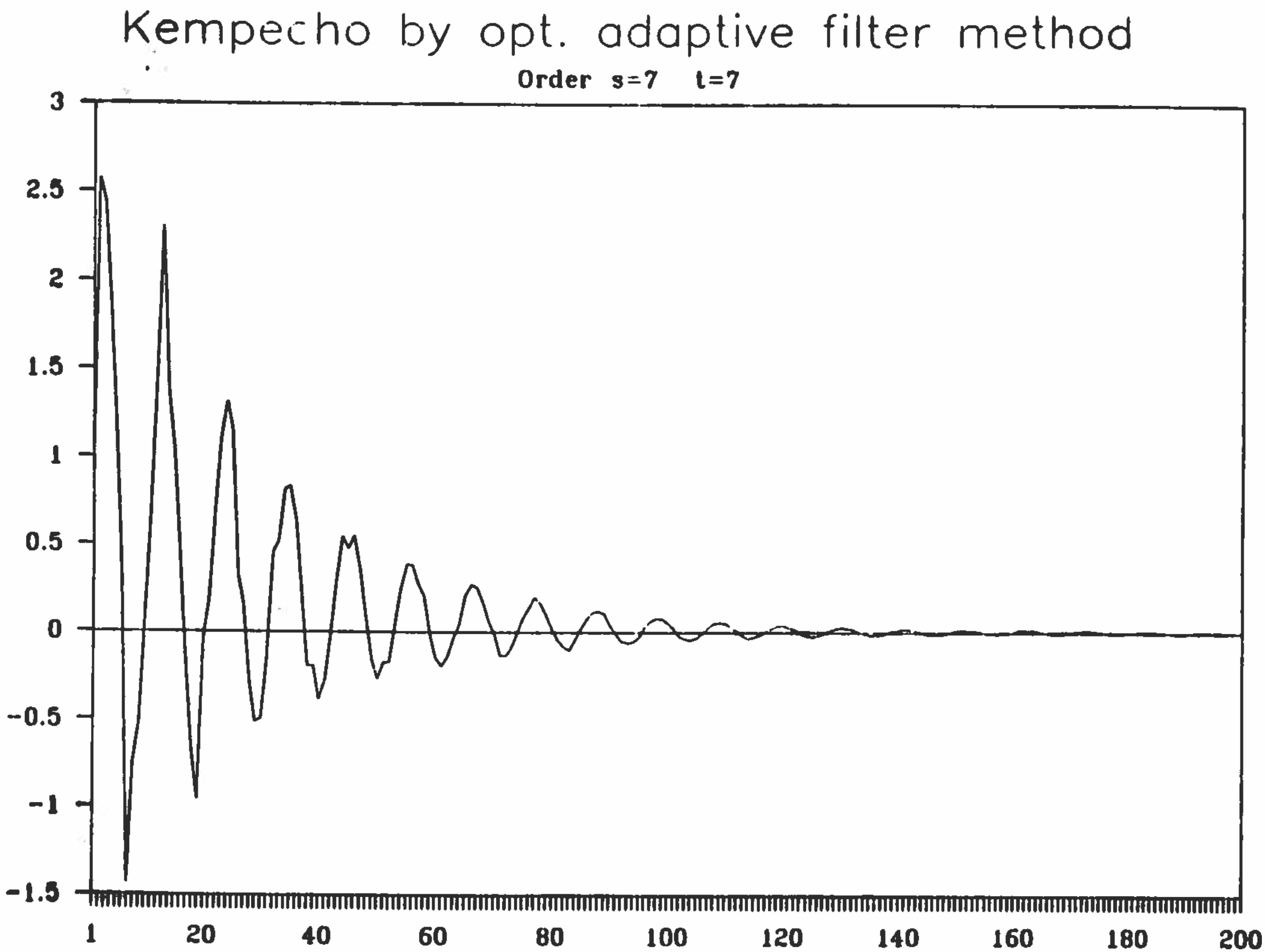


γ = section propagation "constant"

$$= \underbrace{\alpha}_{\text{attenuation}} + \underbrace{\ln z}_{\text{delay}} \quad \Big\} \text{ for cochlea fluid}$$

$$\left.\begin{aligned} \tau &= 1 - \rho \\ \frac{\rho}{\tau} &= \frac{n_0 + n_1 \frac{1}{z} + n_2 \frac{1}{z^2}}{d_0 + d_1 \frac{1}{z} + d_2 \frac{1}{z^2}} \end{aligned}\right\} \text{ dynamics of Basilar membrane, etc.}$$

$\alpha, n_0, n_1, n_2, d_0, d_1, d_2$ vary from section to section and can be estimated using linear estimation theory; they can also be expressed in terms of ear parameters.



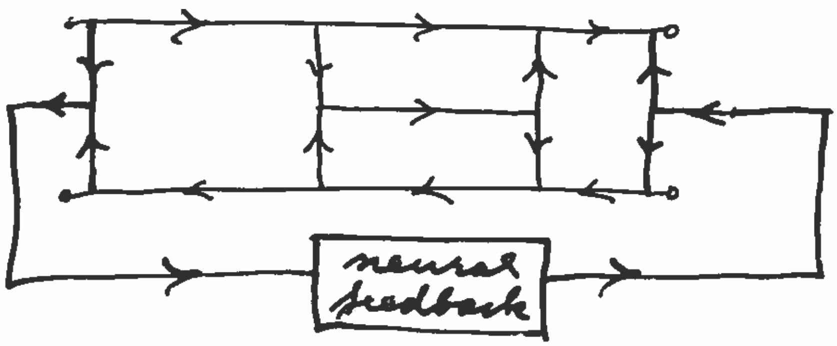
Kempecho by opt. adaptive filter method
Order s=7 t=7
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
1
20
40
60
80
100
120
140
160
180
200

Need for Neural Feedback

Linear Synthesis Filter gives responses somewhat like Kemp echoes, but even with high orders they die out more rapidly. This is due to the "passive" nature of synthesis filters obtained via standard linear estimation theory.

As attributed to Gold in 1948, there may be activity in the auditory system. So we add "neural feedback."

Linear Synthesis Filter with Neural Feedback



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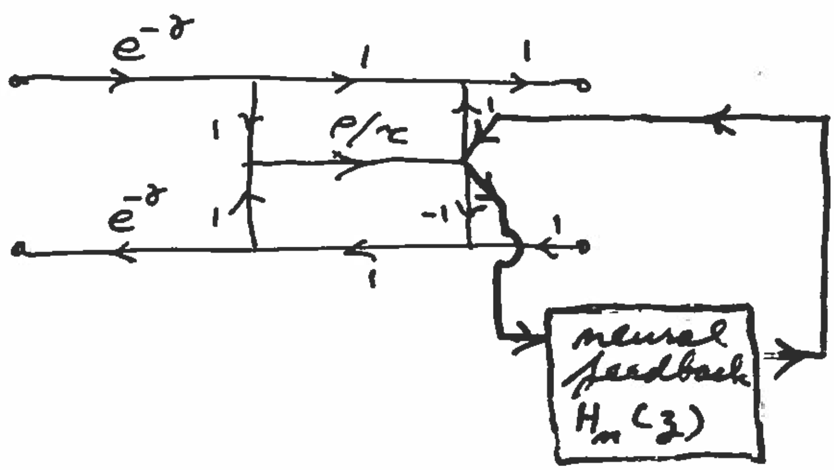


Essentially this replaces ρ/r by

$$\frac{\rho}{r}\left(1 - H_n(z)\right)^{-1}$$

With H_n "active" we can achieve more oscillatory-type responses.

Basic Equations – Linear Case

The linear synthesis filter can be derived from the equations

$$\nabla p = -P(x,s)\, u_v$$
$$\nabla u_v = -\frac{p}{Q(x,s)}$$

where p = pressure difference across Basilar membrane

u_v = scala vestibula "area" velocity $= S_v(x)\, v_v$

$$P(x,s) = \frac{1}{S_v(x)} \cdot \left[R_v + \rho_v \cdot s\right] \quad ; \quad s = \frac{\partial[\cdot]}{\partial t}$$

R_v = coefficient of frictional force in scala vestibula

ρ_v = mass density of fluid in scala vestibula

$S_v(x)$ = cross sectional area of scala vestibula

$$Q(x,s) = \frac{\mu(x)s^2 + \sigma(x)s + \phi(x)}{D(x) \cdot s}$$

$\mu(x)$ = mass per unit area of Basilar membrane

$\sigma(x)$ = friction per unit area for Basilar membrane motion

$\phi(x)$ = spring constant per unit area of Basilar membrane

$D(x)$ = width of Basilar membrane (movable portion).

Nonlinearities

These are due to the interaction of the fluid flow over the Basilar membrane with the motion of the Basilar membrane itself.

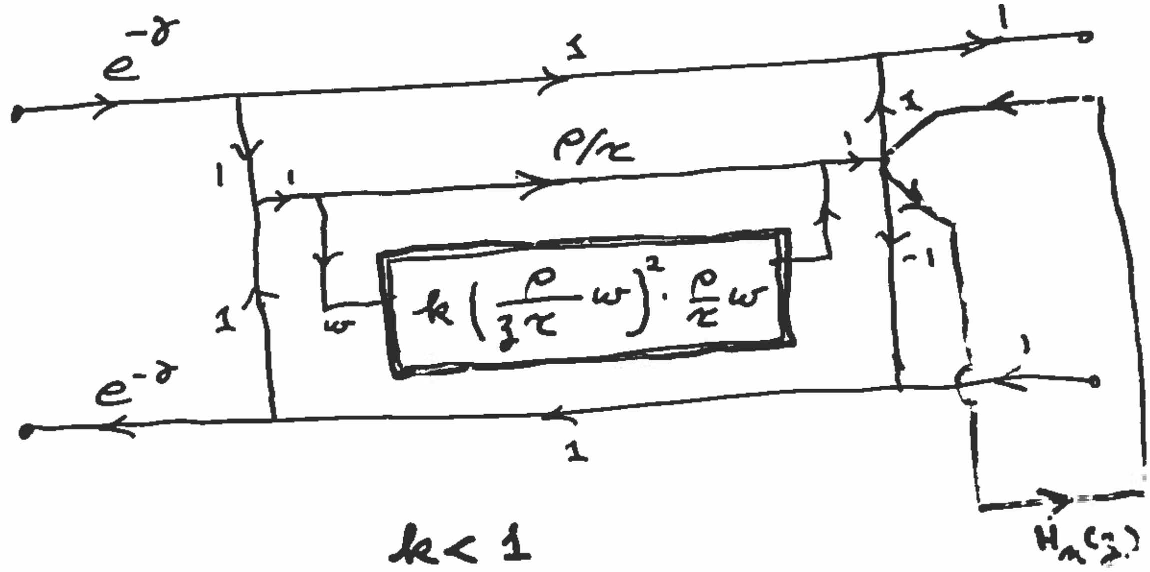
These give rise to

$$\nabla p = -P(x,a)\, u_v$$

$$\nabla u_v = -\Big[1 + \underbrace{\frac{8}{D^4}\Big(\frac{1}{8Q(x,a)}\cdot p\Big)^2}_{\text{nonlinearity}}\Big]\cdot \frac{1}{Q(x,a)}\, p$$

This leads to an added cubic term in the digital synthesis filter.

Nonlinear Synthesis Filter



$k < 1$

$$H_n(z) \approx \frac{a_0 + a_1 \, {}^{1}/_{z}}{b_0 + b_1 \, {}^{1}/_{z}}$$