DSP-CIS

Part-II : Filter Design & Implementation

Chapter-5 : Filter Realization

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Filter Design Process

- **Step-1 : Define filter specs**
  Pass-band, stop-band, optimization criterion,…
- **Step-2 : Derive optimal transfer function**
  FIR or IIR design — **Chapter-4**
- **Step-3 : Filter realization** (block scheme/flow graph)
  Direct form realizations, lattice realizations,… — **Chapter-5**
- **Step-4 : Filter implementation** (software/hardware)
  Finite word-length issues, … — **Chapter-6**
  Question: implemented filter = designed filter ?
  'You can't always get what you want' -Jagger/Richards (?)

Chapter-5 : Filter Realization

- **FIR Filter Realization**
- **IIR Filter Realization**

PS: Will always assume *real-valued* filter coefficients

PS:

Q:Why bother
about many different realizations for one and the same filter?

A: See Chapter-6 !

FIR Filter Realization

FIR Filter Realization

=Construct (realize) LTI system (with delay elements, adders and multipliers), such that I/O behavior is given by..

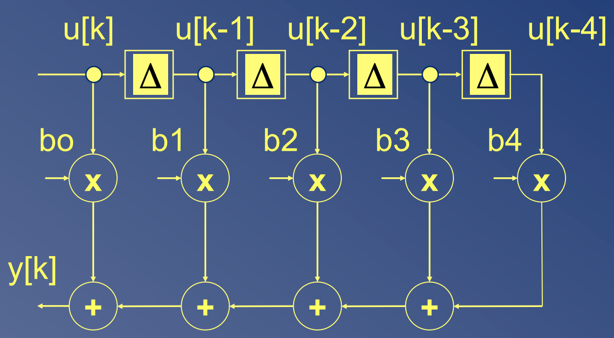
$$y[k] = b_0.u[k] + b_1.u[k-1] + ... + b_L.u[k-L]$$

Several possibilities exist…

1. Direct form
2. Transposed direct form
3. Lattice realization (LPC lattice)
4. Lossless lattice realization
5. Frequency-domain realization: see Part-IV

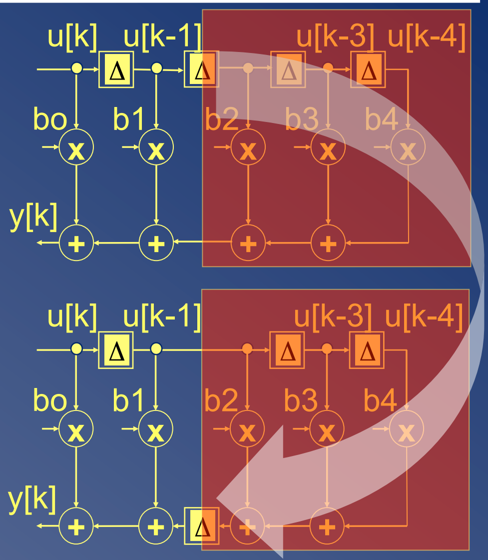
FIR / 1. Direct Form

$$y[k] = b_0.u[k] + b_1.u[k-1] + \ldots + b_L.u[k-L]$$



FIR / 2. Transposed Direct Form

Starting point is direct form :

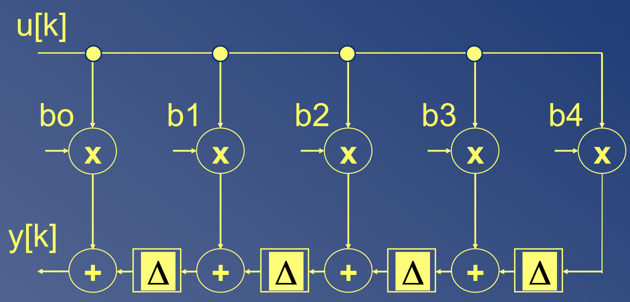


`Retiming' =

select subgraph (shaded)
remove one delay element on all inbound arrows
add one delay element on all outbound arrows

FIR / 2. Transposed Direct Form

`Retiming' : repeated application results in...



i.e. `transposed direct form ' (named after 'transposed' state space model)

(=different software/hardware (`pipeline delays'), same i/o-behavior)

FIR / 3. Lattice Realization

Derived from combined realization of…

$$H(z): \quad y[k] = b_0.u[k] + b_1.u[k-1] + \ldots + b_L.u[k-L]$$

…with `flipped' version of H(z)

$$\tilde{H}(z) = z^{-L}.H(z^{-1}): \quad \tilde{y}[k] = b_L.u[k] + b_{L-1}.u[k-1] + \ldots + b_0.u[k-L]$$

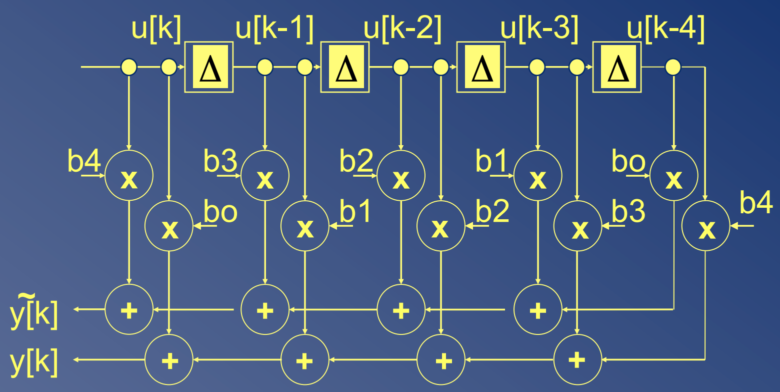
Reversed (real-valued) coefficient vector results in...

$$\left|\tilde{H}(z)\right|^2_{z=e^{j\omega}} = \tilde{H}(z).\tilde{H}(z^{-1})\Big|_{z=e^{j\omega}} = \ldots = \left|H(z)\right|^2_{z=e^{j\omega}}$$

i.e. - same magnitude response
- different phase response

FIR / 3. Lattice Realization

Starting point is direct form realization…



Now 1 page of maths…

FIR / 3. Lattice Realization

$$\begin{bmatrix}\tilde{Y}(z)\\ Y(z)\end{bmatrix} = \begin{bmatrix} b_4 & b_3 & b_2 & b_1 & b_0 \\ b_0 & b_1 & b_2 & b_3 & b_4\end{bmatrix}.\begin{bmatrix}1 & z^{-1} & \dots & z^{-4}\end{bmatrix}^T.U(z)$$

With $\kappa_0 = \frac{b_4}{b_0}$ if $(b_0 \neq 0)$ and $(|\kappa_0| \neq 1)$ this can be rewritten as

$$\begin{bmatrix}\tilde{Y}(z)\\ Y(z)\end{bmatrix} = \begin{bmatrix} 1 & \kappa_0 \\ \kappa_0 & 1\end{bmatrix}\begin{bmatrix} 0 & b'_3 & b'_2 & b'_1 & b'_0 \\ b'_0 & b'_1 & b'_2 & b'_3 & 0\end{bmatrix}.\begin{bmatrix}1 & z^{-1} & \dots & z^{-4}\end{bmatrix}^T.U(z)$$

$$= \begin{bmatrix} 1 & \kappa_0 \\ \kappa_0 & 1\end{bmatrix}.\begin{bmatrix} z^{-1} & 0 \\ 0 & 1\end{bmatrix}.\begin{bmatrix} b'_3 & b'_2 & b'_1 & b'_0 \\ b'_0 & b'_1 & b'_2 & b'_3\end{bmatrix}.\begin{bmatrix}1 & z^{-1} & \dots & z^{-3}\end{bmatrix}^T.U(z)$$

order reduction

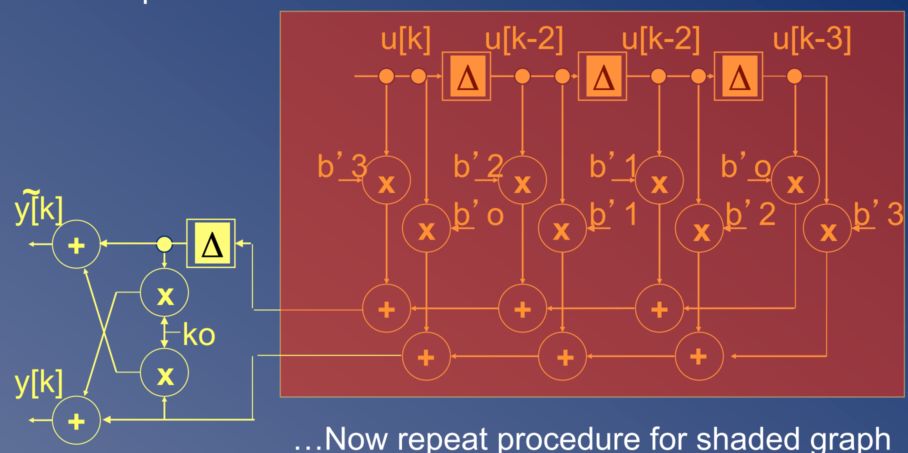
$$b'_0 = b_0, \quad b'_1 = \frac{b_1 - \kappa_0 b_3}{1-\kappa_0^2}, \quad b'_2 = \frac{b_2 - \kappa_0 b_2}{1-\kappa_0^2}, \quad b'_3 = \frac{b_3 - \kappa_0 b_1}{1-\kappa_0^2}$$

PS: find fix for case bo=0

PS: if |ko|=1, then transformation matrix $\begin{bmatrix} 1 & \kappa_0 \\ \kappa_0 & 1\end{bmatrix}$ is rank-deficient

FIR / 3. Lattice Realization

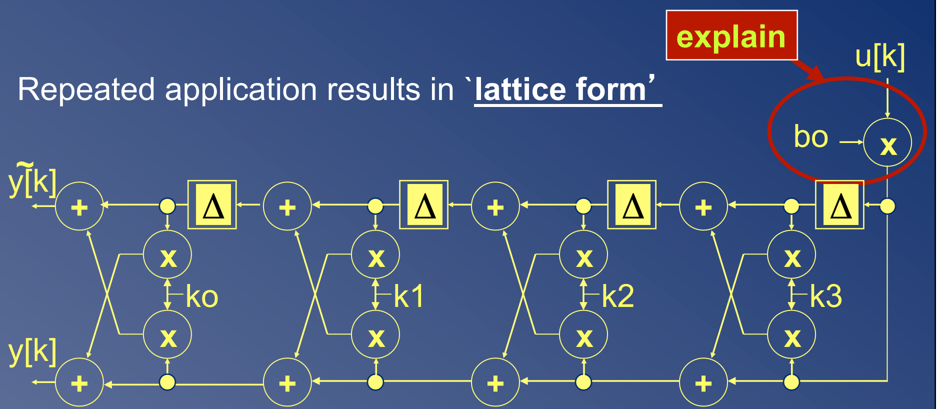
This is equivalent to...



...Now repeat procedure for shaded graph
(=same structure as the one we started from)

FIR / 3. Lattice Realization

Repeated application results in `**lattice form**'



(= different software/hardware, same i/o-behavior)

FIR / 3. Lattice Realization

- Also known as `linear predictive coding (LPC) lattice'
  K_i's are so-called `**reflection coefficients**'
  Every set of b_i's corresponds to a set of K_i's, and vice versa
- Procedure for computing K_i's from b_i's corresponds to the well-known `**Schur-Cohn' stability test** (from control theory):
  Problem = for a given polynomial B(z), how do we find out if all the zeros of B(z) are 'stable' (i.e. lie inside unit circle) ?
  Solution = from bi's, compute reflection coefficients Ki's (=procedure on previous slides). Zeros are (proved to be) stable iff all Ki's statisfy |Ki|<1 !
- Procedure (page 10) breaks down if |Ki|=1 is encountered. Then have to select other realization (direct form, lossless lattice, …) for B(z)
- Lattice form not overly relevant at this point, but sets stage for similar derivations that lead to more relevant realizations (read on…)

FIR / 4. Lossless Lattice Realization

Derived from combined realization of H(z)…

$$H(z): \quad y[k] = b_0.u[k] + b_1.u[k-1] + \ldots + b_L.u[k-L]$$

…with

$$\tilde{\tilde{H}}(z): \quad \tilde{\tilde{y}}[k] = \tilde{\tilde{b}}_0.u[k] + \tilde{\tilde{b}}_1.u[k-1] + \ldots + \tilde{\tilde{b}}_L.u[k-L]$$

…which is such that

$$H(z).H(z^{-1}) + \tilde{\tilde{H}}(z).\tilde{\tilde{H}}(z^{-1}) = 1 \qquad (*)$$

PS : Interpretation ?… (see next slide)

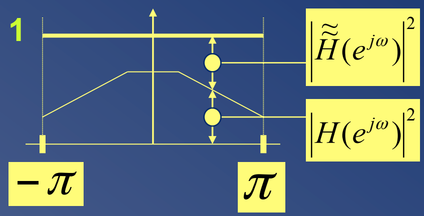
PS : May have to scale H(z) to achieve this (why?) (scaling omitted here)

FIR / 4. Lossless Lattice Realization

PS : Interpretation ?

When evaluated on the unit circle, formula (*) is equivalent to (for filters with real-valued coefficients)

$$\left|H(z)\right|^2_{z=e^{j\omega}} + \left|\tilde{\tilde{H}}(z)\right|^2_{z=e^{j\omega}} = 1$$



i.e. $H(z)$ and $\tilde{\tilde{H}}(z)$ are `power complementary'
(= form a 1-input/2-output `lossless' system, see also below)

FIR / 4. Lossless Lattice Realization

PS : How is $\tilde{\tilde{H}}(z)$ computed ?

$$\tilde{\tilde{H}}(z).\tilde{\tilde{H}}(z^{-1}) = \underbrace{1 - H(z).H(z^{-1})}_{R(z)}$$

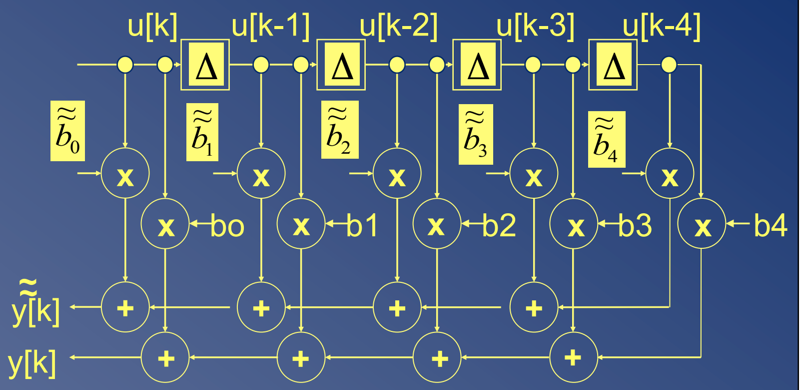
Note that if z_i (and z_i^*) is a root of R(z), then $1/z_i$ (and $1/z_i^*$) is also a root of R(z). Hence can factorize R(z) as…

$$\tilde{\tilde{H}}(z).\tilde{\tilde{H}}(z^{-1}) = \alpha^2 \prod_i (z^{-1} - z_i)(z - z_i) \rightarrow \tilde{\tilde{H}}(z) = \alpha \prod_i (z^{-1} - z_i)$$

Note that z_i's can be selected such that all roots of $\tilde{\tilde{H}}(z)$ lie inside the unit circle, i.e. $\tilde{\tilde{H}}(z)$ is a minimum-phase FIR filter.
This is referred to as spectral factorization, $\tilde{\tilde{H}}(z)$ =spectral factor.

FIR / 4. Lossless Lattice Realization

Starting point is direct form realization…



Now 1 page of maths…

FIR / 4. Lossless Lattice Realization

$$\begin{bmatrix} \tilde{\tilde{Y}}(z) \\ Y(z) \end{bmatrix} = \begin{bmatrix} \tilde{\tilde{b}}_0 & \tilde{\tilde{b}}_1 & \tilde{\tilde{b}}_2 & \tilde{\tilde{b}}_3 & \tilde{\tilde{b}}_4 \\ b_0 & b_1 & b_2 & b_3 & b_4 \end{bmatrix} . \begin{bmatrix} 1 & z^{-1} & \ldots & z^{-4} \end{bmatrix}^T . U(z)$$

From (*) (page 14), it follows that (**)

$$b_0.b_4 + \tilde{\tilde{b}}_0.\tilde{\tilde{b}}_4 = 0 \quad \Rightarrow \quad \begin{bmatrix} \tilde{\tilde{b}}_0 & b_0 \end{bmatrix} . \begin{bmatrix} \tilde{\tilde{b}}_4 \\ b_4 \end{bmatrix} = 0 \quad \Rightarrow \quad \begin{bmatrix} \tilde{\tilde{b}}_0 \\ b_0 \end{bmatrix} \perp \begin{bmatrix} \tilde{\tilde{b}}_4 \\ b_4 \end{bmatrix}$$

= orthogonal vectors

Hence there exists a rotation angle θo such that

$$\begin{bmatrix} \tilde{\tilde{Y}}(z) \\ Y(z) \end{bmatrix} = \begin{bmatrix} \cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0 \end{bmatrix} \begin{bmatrix} \underline{\underline{0}} & \tilde{\tilde{b}}'_0 & \tilde{\tilde{b}}'_1 & \tilde{\tilde{b}}'_2 & \tilde{\tilde{b}}'_3 \\ b'_0 & b'_1 & b'_2 & b'_3 & \underline{\underline{0}} \end{bmatrix} . \begin{bmatrix} 1 & z^{-1} & \ldots & z^{-4} \end{bmatrix}^T . U(z)$$

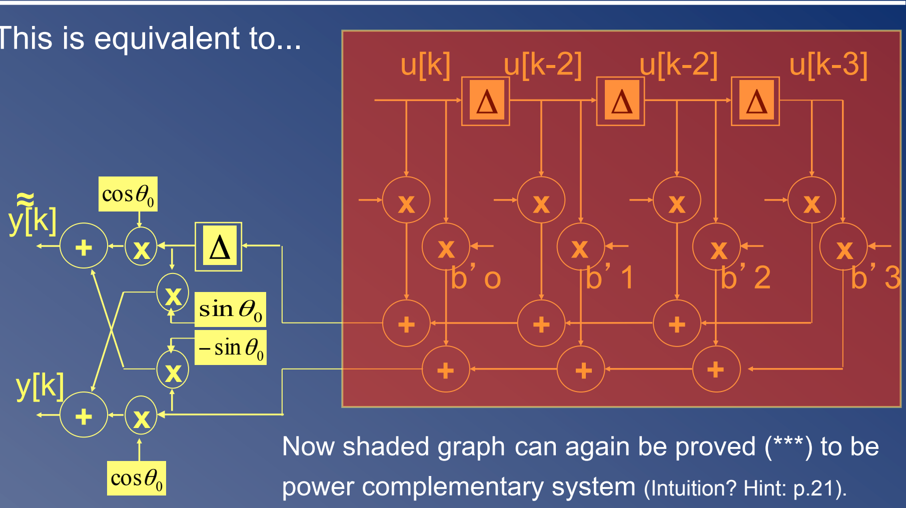
$$= \begin{bmatrix} \cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0 \end{bmatrix} . \begin{bmatrix} z^{-1} & 0 \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} \tilde{\tilde{b}}'_0 & \tilde{\tilde{b}}'_1 & \tilde{\tilde{b}}'_2 & \tilde{\tilde{b}}'_3 \\ b'_0 & b'_1 & b'_2 & b'_3 \end{bmatrix} \begin{bmatrix} 1 & z^{-1} & \ldots & z^{-3} \end{bmatrix}^T . U(z)$$

order reduction

(**) $1 = H(z).H(z^{-1}) + \tilde{\tilde{H}}(z).\tilde{\tilde{H}}(z^{-1}) = \underbrace{(b_0.b_4 + \tilde{\tilde{b}}_0.\tilde{\tilde{b}}_4)}_{0}.(z^4 + z^{-4}) + \underbrace{(..)}_{0}.(z^3 + z^{-3}) + \ldots + \underbrace{(..)}_{1}.z^0$

FIR / 4. Lossless Lattice Realization

This is equivalent to...



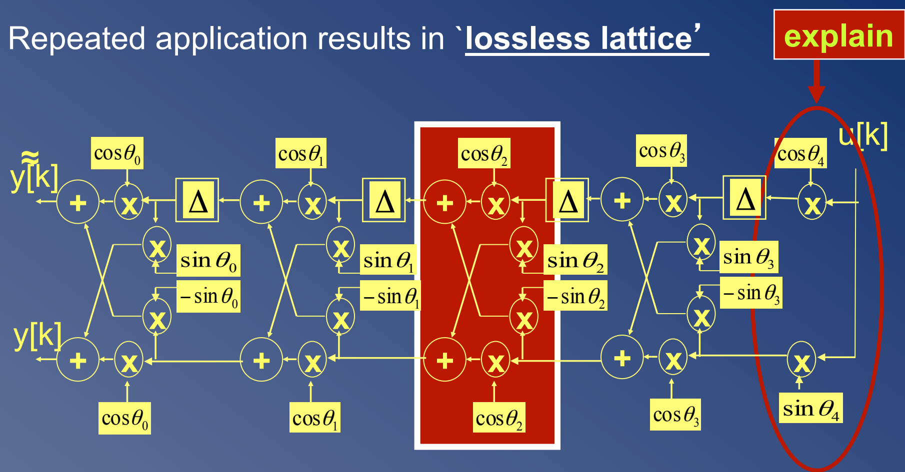
Now shaded graph can again be proved (***) to be power complementary system (Intuition? Hint: p.21).

Hence can repeat procedure…

$$(***)\quad 1=\begin{bmatrix}\tilde{\tilde{H}}(z^{-1}) & H(z^{-1})\end{bmatrix}\cdot\begin{bmatrix}\tilde{\tilde{H}}(z)\\ H(z)\end{bmatrix}=\begin{bmatrix}\tilde{\tilde{H}}_{\otimes}(z^{-1}) & H_{\otimes}(z^{-1})\end{bmatrix}\cdot\begin{bmatrix}z & 0\\ 0 & 1\end{bmatrix}\cdot\begin{bmatrix}\cos\theta_0 & \sin\theta_0\\ -\sin\theta_0 & \cos\theta_0\end{bmatrix}\cdot\begin{bmatrix}\cos\theta_0 & -\sin\theta_0\\ \sin\theta_0 & \cos\theta_0\end{bmatrix}\cdot\begin{bmatrix}z^{-1} & 0\\ 0 & 1\end{bmatrix}\cdot\begin{bmatrix}\tilde{\tilde{H}}_{\otimes}(z)\\ H_{\otimes}(z)\end{bmatrix}=\begin{bmatrix}\tilde{\tilde{H}}_{\otimes}(z^{-1}) & H_{\otimes}(z^{-1})\end{bmatrix}\cdot\begin{bmatrix}\tilde{\tilde{H}}_{\otimes}(z)\\ H_{\otimes}(z)\end{bmatrix}$$

FIR / 4. Lossless Lattice Realization

Repeated application results in `**lossless lattice**'



FIR / 4. Lossless Lattice Realization

Lossless lattice :

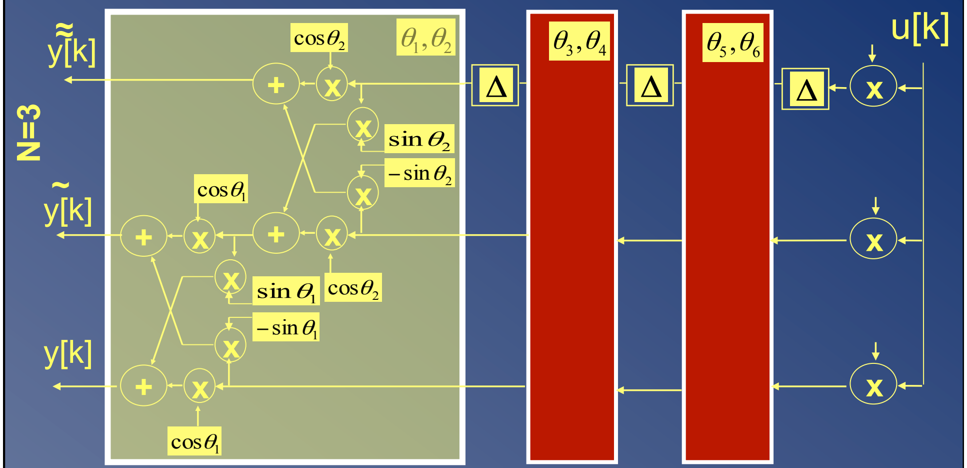
- Also known as `paraunitary lattice'
- Each **2-input/2-output section** is based on an orthogonal transformation, which preserves norm/energy/power

$$\begin{bmatrix} OUT_1 \\ OUT_2 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} IN_1 \\ IN_2 \end{bmatrix} \Rightarrow (IN_1)^2 + (IN_2)^2 = (OUT_1)^2 + (OUT_2)^2$$

i.e. forms a 2-input/2-output `lossless' system (=time-domain view)
Overall system is realized as cascade of lossless sections (+delays), hence is itself also `lossless' (see p.15, =freq-domain view)

FIR / 4. Lossless Lattice Realization

PS : Can be generalized to 1-input N-output lossless systems
(will be used in Part-IV) (compare to p.20 !)



$H(z).H(z^{-1}) + \tilde{H}(z).\tilde{H}(z^{-1}) + \tilde{\tilde{H}}(z).\tilde{\tilde{H}}(z^{-1}) = 1$ **explain/derive!**

IIR Filter Realization

IIR Filter Realization

=Construct (realize) LTI system (with delay elements, adders and multipliers), such that I/O behavior is given by..

$$H(z)=\frac{B(z)}{A(z)}=\frac{b_0+b_1z^{-1}+...+b_Lz^{-L}}{1+a_1z^{-1}+...+a_Lz^{-L}}$$

Several possibilities exist…

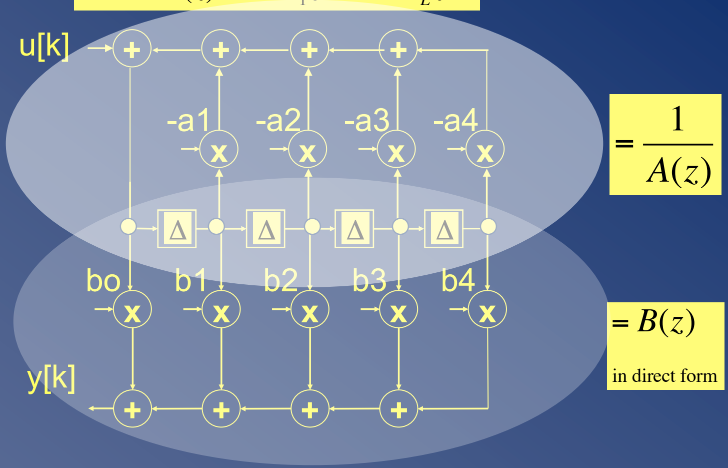
1. Direct form
2. Transposed direct form

<u>PS</u>: Parallel and cascade realization

4. Lattice-ladder realization
5. Lossless lattice realization

IIR / 1. Direct Form

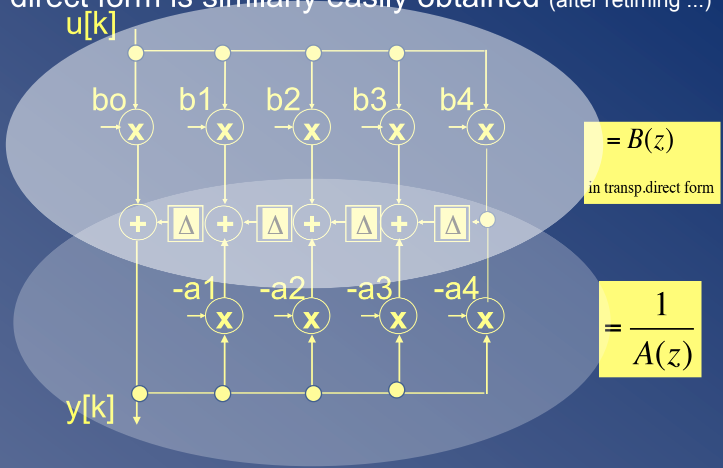
$$H(z)=\frac{B(z)}{A(z)}=\frac{b_0+b_1z^{-1}+...+b_Lz^{-L}}{1+a_1z^{-1}+...+a_Lz^{-L}}$$



<u>PS</u> : If all ai=0 (i.e. H(z) is FIR), then this reduces to a <u>direct form FIR</u>

IIR / 2. Transposed Direct Form

Transposed direct form is similarly easily obtained (after retiming ...)



PS : If all ai=0 (i.e. H(z) is FIR), then this reduces to a transposed direct form FIR

IIR / PS: Parallel & Cascade Realization

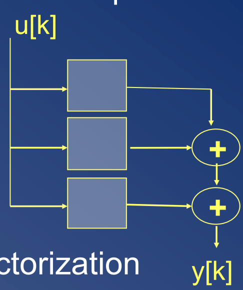
- Parallel realization based on partial fraction decomposition

For simple poles →

$$H(z)=\frac{B(z)}{A(z)}=c_0+\sum_{i=1}^{L_1}\frac{\alpha_i}{1+\beta_i z^{-1}}+\sum_{i=1}^{L_2}\frac{\gamma_1+\delta_i z^{-1}}{1+\varepsilon_1 z^{-1}+\varphi_N z^{-2}}$$

  - Each term realized in, e.g., direct form
  - Transmission zeros are realized iff signals from different sections exactly cancel out

    (=difficult in finite word-length implementation)



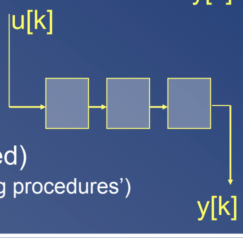
- Cascade realization based on pole-zero factorization

For L even →

$$H(z)=\frac{B(z)}{A(z)}=b_0.\prod_{i=1}^{L/2}\frac{1+\alpha_i.z^{-1}+\beta_i.z^{-2}}{1+\gamma_i.z^{-1}+\delta_i.z^{-2}}$$

  - Each section('biquad') realized in, e.g., direct form
  - Cascade realization is not unique (details omitted)

    (=multiple ways of pairing poles and zeros (need for 'pairing procedures') and multiple ways of ordering sections in cascade)



IIR / 3. Lattice-Ladder Realization

Derived from combined realization of

$$H(z)=\frac{B(z)}{A(z)}=\frac{b_0+b_1z^{-1}+...+b_Lz^{-L}}{1+a_1z^{-1}+...+a_Lz^{-L}}$$

with…

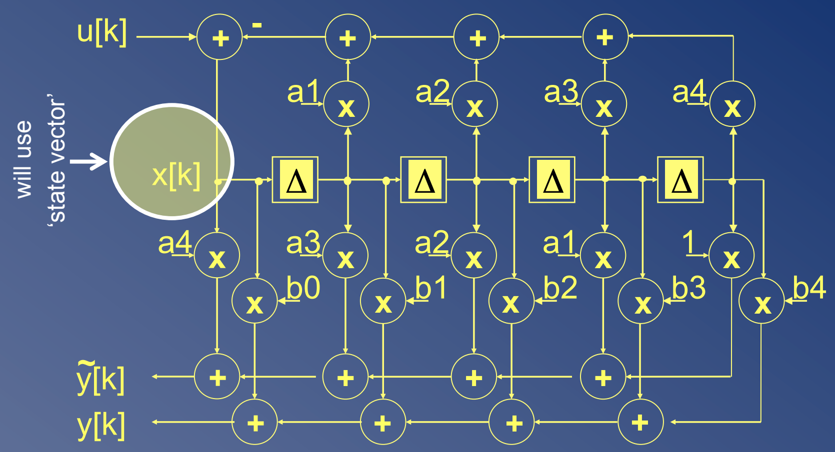
$$\tilde{H}(z)=\frac{\tilde{A}(z)}{A(z)}=\frac{a_L+a_{L-1}z^{-1}+...+1.z^{-L}}{1+a_1z^{-1}+...+a_Lz^{-L}}$$

- Numerator polynomial is denominator polynomial with reversed coefficient vector (see also p.8)
- Hence $\tilde{H}(z)$ is an \`all-pass' (=\`SISO lossless') filter :

$$\tilde{H}(z).\tilde{H}(z^{-1})=1 \qquad \left|\tilde{H}(z)\right|^2_{z=e^{j\omega}}=\frac{\left|\tilde{A}(z)\right|^2_{z=e^{j\omega}}}{\left|A(z)\right|^2_{z=e^{j\omega}}}=1$$

IIR / 3. Lattice-Ladder Realization

Starting point is direct form realization…

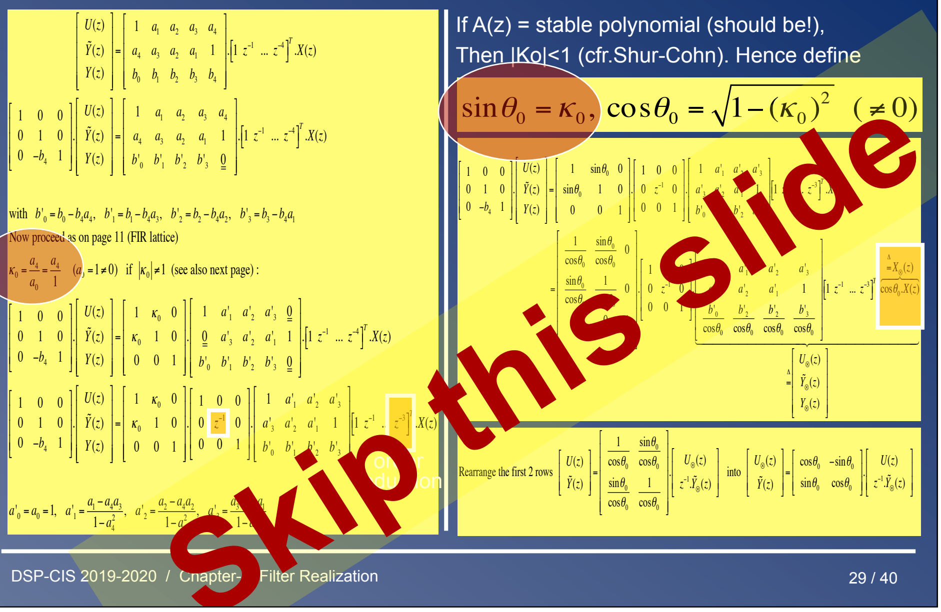


Now 1 page (full) of maths…

IIR / 3. Lattice-Ladder Realization

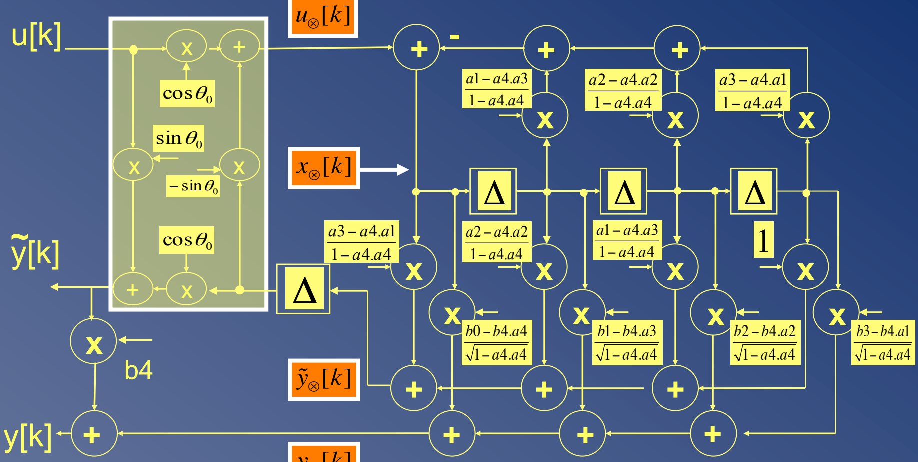
If A(z) = stable polynomial (should be!),
Then |Ko|<1 (cfr.Shur-Cohn). Hence define

$$\sin\theta_0 = \kappa_0,\ \cos\theta_0 = \sqrt{1-(\kappa_0)^2} \quad (\neq 0)$$



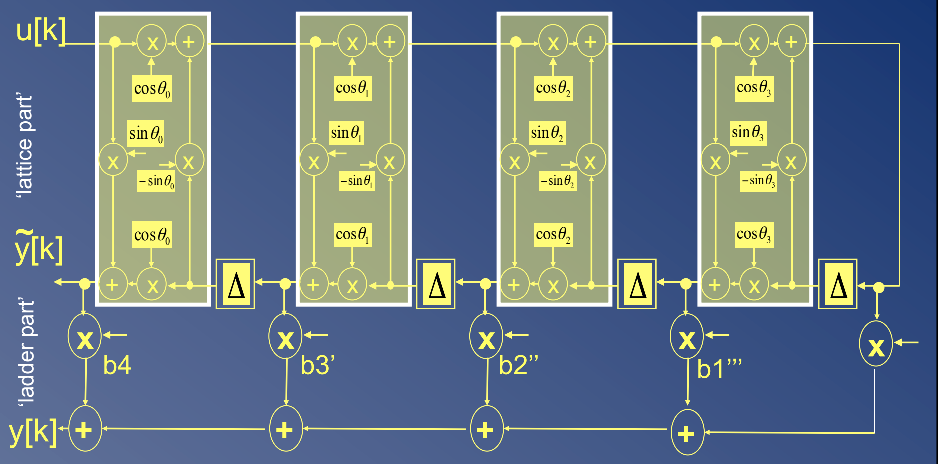
IIR / 3. Lattice-Ladder Realization

Then this is equivalent to…



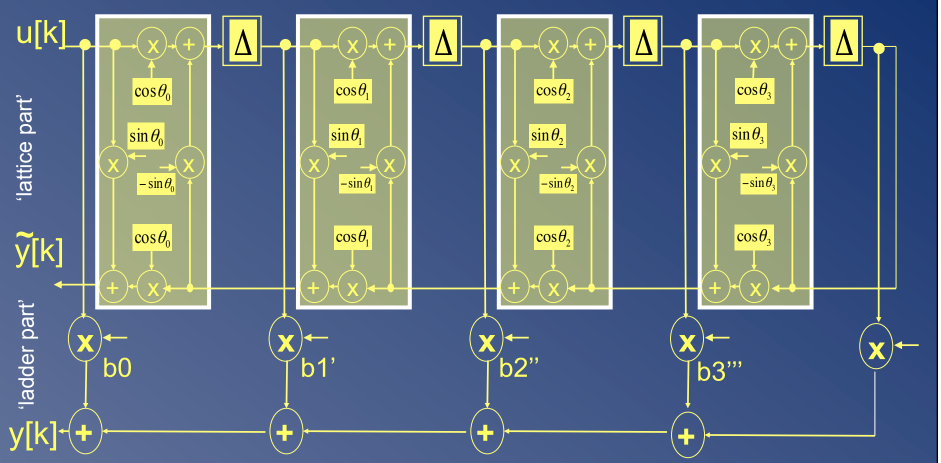
IIR / 3. Lattice-Ladder Realization

Procedure can be repeated (explain), leads to `lattice-ladder form'



IIR / 3. Lattice-Ladder Realization

PS: Similar derivation leads to 2nd 'lattice-ladder' form



IIR / 3. Lattice-Ladder Realization

- K_i's **(=sin(theta$_i$) !)** are `reflection coefficients'
- Procedure for computing K_i's from a_i's again corresponds to **`Schur-Cohn' stability test**
- Orthogonal transformations correspond to 2-input/2-output `lossless' sections (=time-domain view).

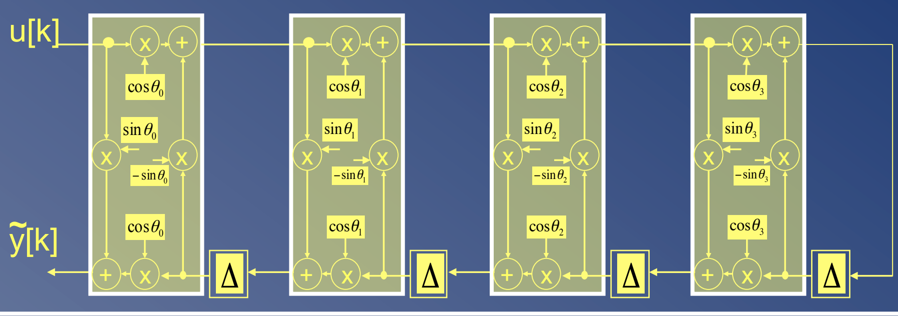
$$\begin{bmatrix} OUT_1 \\ OUT_2 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} IN_1 \\ IN_2 \end{bmatrix} \Rightarrow (IN_1)^2 + (IN_2)^2 = (OUT_1)^2 + (OUT_2)^2$$

Cascade of lossless sections (+delays) is also `lossless', i.e. `all-pass' (see p.27, =freq-domain view)

IIR / 3. Lattice-Ladder Realization

PS : Note that the all-pass part corresponds to A(z) (i.e. L angles θ_i correspond to L coeffs a_i) while the ladder part corresponds to B(z). If all a_i=0 (i.e. H(z) is FIR), then all θ_i=0, hence the all-pass part reduces to a delay line, and the lattice-ladder form reduces to a **direct-form FIR**.

PS : `All-pass' part (SISO u[k]->$\tilde{y}$[k]) is known as **`Gray-Markel'** structure



IIR / 4. Lossless Lattice Realization

Derived from combined realization of (possibly rescaled, as on p.14)

$$H(z) = \frac{B(z)}{A(z)} = \frac{b_0 + b_1 z^{-1} + ... + b_L z^{-L}}{1 + a_1 z^{-1} + ... + a_L z^{-L}}$$

with...

$$\tilde{\tilde{H}}(z) = \frac{\tilde{\tilde{B}}(z)}{A(z)} = \frac{\tilde{\tilde{b}}_0 + \tilde{\tilde{b}}_1 . z^{-1} + ... + \tilde{\tilde{b}}_L . z^{-L}}{1 + a_1 z^{-1} + ... + a_L z^{-L}}$$

such that…

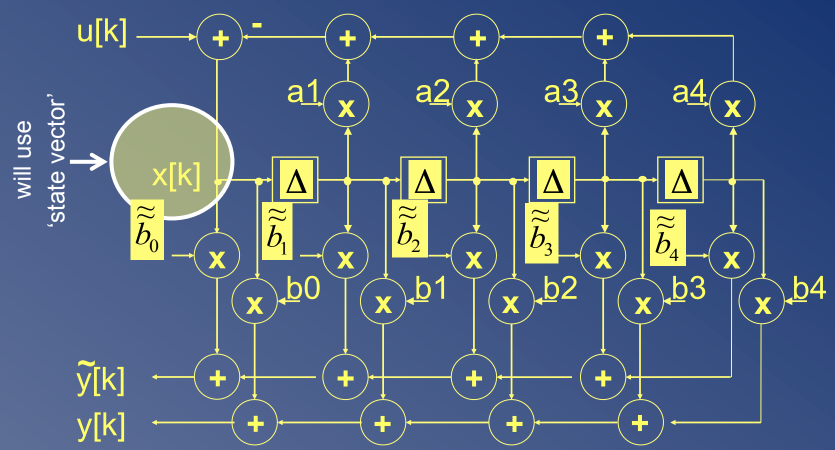
$$H(z).H(z^{-1}) + \tilde{\tilde{H}}(z).\tilde{\tilde{H}}(z^{-1}) = 1 \qquad (**)$$

$$\Rightarrow B(z).B(z^{-1}) + \tilde{\tilde{B}}(z).\tilde{\tilde{B}}(z^{-1}) = A(z).A(z^{-1})$$

i.e. $\tilde{\tilde{H}}(z)$ and $H(z)$ are `power complementary' (p.15)

IIR / 4. Lossless Lattice Realization

Starting point is direct form realization…



Now 1 page (full) of maths…

IIR / 4. Lossless Lattice Realization

$$\begin{bmatrix} U(z) \\ \tilde{Y}(z) \\ Y(z) \end{bmatrix} = \begin{bmatrix} a_0 & a_1 & a_2 & a_3 & a_4 \\ \tilde{\tilde{b}}_0 & \tilde{\tilde{b}}_1 & \tilde{\tilde{b}}_2 & \tilde{\tilde{b}}_3 & \tilde{\tilde{b}}_4 \\ b_0 & b_1 & b_2 & b_3 & b_4 \end{bmatrix} \cdot \begin{bmatrix} 1 & z^{-1} & \ldots & z^{-4} \end{bmatrix}^T . X(z)$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi_0 & -\sin\psi_0 \\ 0 & \sin\psi_0 & \cos\psi_0 \end{bmatrix} \cdot \begin{bmatrix} a_0 & a_1 & a_2 & a_3 & a_4 \\ \tilde{\tilde{b}}'_0 & \tilde{\tilde{b}}'_1 & \tilde{\tilde{b}}'_2 & \tilde{\tilde{b}}'_3 & \tilde{\tilde{b}}'_4 \\ b'_0 & b'_1 & b'_2 & b'_3 & \underline{\underline{0}} \end{bmatrix} \cdot \begin{bmatrix} 1 & z^{-1} & \ldots & z^{-4} \end{bmatrix}^T . X(z)$$

for $\frac{\sin\psi_0}{\cos\psi_0} = \frac{b_4}{\tilde{\tilde{b}}_4}$ and $\tilde{\tilde{b}}'_4 = \sqrt{(\tilde{\tilde{b}}_4)^2 + (b_4)^2}$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi_0 & -\sin\psi_0 \\ 0 & \sin\psi_0 & \cos\psi_0 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{\cos\theta_0} & \frac{\sin\theta_0}{\cos\theta_0} & 0 \\ \frac{\sin\theta_0}{\cos\theta_0} & \frac{1}{\cos\theta_0} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} a'_0 & a'_1 & a'_2 & a'_3 & \underline{\underline{0}} \\ \tilde{\tilde{b}}''_0 & \tilde{\tilde{b}}''_1 & \tilde{\tilde{b}}''_2 & \tilde{\tilde{b}}''_3 & \tilde{\tilde{b}}''_4 \\ b'_0 & b'_1 & b'_2 & b'_3 & \underline{\underline{0}} \end{bmatrix} \cdot \begin{bmatrix} 1 & z^{-1} & \ldots & z^{-4} \end{bmatrix}^T . X(z)$$

for $\sin\theta_0 = \frac{a_4}{\tilde{\tilde{b}}'_4} = \frac{a_4}{\sqrt{(\tilde{\tilde{b}}_4)^2 + (b_4)^2}}$ (o) and $\tilde{\tilde{b}}''_4 = \ldots = \sqrt{(\tilde{\tilde{b}}_4)^2 + (b_4)^2 - (a_4)^2}$

PS: right-hand side of (o) has modulus <1 (hence |sinθo|≠1, cosθo≠0) which follows from 'modulus property' for (**) p.35:

if (**) for $\begin{bmatrix} H(z) & \tilde{\tilde{H}}(z) \end{bmatrix}$ non-constant (i.e. order ≥ 1) and for A(z) stable, then:

$|H(z=0)|^2 + |\tilde{\tilde{H}}(z=0)|^2 > 1 \quad \Rightarrow \quad (\frac{b_4}{a_4})^2 + (\frac{\tilde{\tilde{b}}_4}{a_4})^2 > 1 \Rightarrow \left| \frac{a_4}{\sqrt{(\tilde{\tilde{b}}_4)^2 + (b_4)^2}} \right| < 1$

Now it is proved that $\tilde{\tilde{b}}''_0 = 0$

From (**) p.35 it follows that

$$b_0.b_4 + \tilde{\tilde{b}}_0.\tilde{\tilde{b}}_4 = a_0.a_4 \quad \Rightarrow \quad \begin{bmatrix} a_0 & \tilde{\tilde{b}}_0 & b_0 \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} a_4 \\ \tilde{\tilde{b}}_4 \\ b_4 \end{bmatrix} = 0$$

'orthogonal' vectors

$\Rightarrow$ ... plug in transformation with θ_0 and ψ_0...

$$\Rightarrow \begin{bmatrix} a'_0 & \tilde{\tilde{b}}''_0 & b'_0 \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ \tilde{\tilde{b}}''_4 \\ 0 \end{bmatrix} = 0$$

$\Rightarrow \tilde{\tilde{b}}''_0 = 0 \quad (\text{cfr. } \tilde{\tilde{b}}''_4 \neq 0)$

This leads to

$$\begin{bmatrix} U(z) \\ \tilde{Y}(z) \\ Y(z) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi_0 & -\sin\psi_0 \\ 0 & \sin\psi_0 & \cos\psi_0 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{\cos\theta_0} & \frac{\sin\theta_0}{\cos\theta_0} & 0 \\ \frac{\sin\theta_0}{\cos\theta_0} & \frac{1}{\cos\theta_0} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & z^{-1} & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} a'_0 & a'_1 & a'_2 & a'_3 \\ \tilde{\tilde{b}}''_1 & \tilde{\tilde{b}}''_2 & \tilde{\tilde{b}}''_3 & \tilde{\tilde{b}}''_4 \\ b'_0 & b'_1 & b'_2 & b'_3 \end{bmatrix} \cdot \begin{bmatrix} 1 & z^{-1} & \ldots & z^{-3} \end{bmatrix}^T . X(z)$$

order reduction

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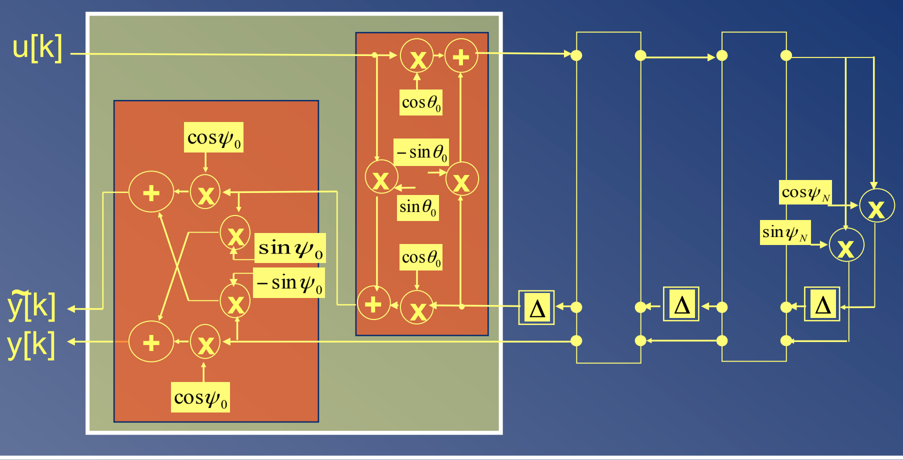
Rearranging rows, etc.., and repeating the order-reduction process, leads to…



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- Orthogonal transformations correspond to (3-input 3-output) \`lossless sections ‘

$$\begin{bmatrix} OUT_1 \\ OUT_2 \\ OUT_3 \end{bmatrix} = \begin{bmatrix} . & . & . \\ . & . & . \\ . & . & . \end{bmatrix} \begin{bmatrix} IN_1 \\ IN_2 \\ IN_3 \end{bmatrix}$$

$$\Rightarrow (IN_1)^2 + (IN_2)^2 + (IN_3)^2 = (OUT_1)^2 + (OUT_2)^2 + (OUT_3)^2$$

  Overall system is realized as cascade of lossless sections (+delays), hence is itself also \`lossless ‘

- **PS** : If all a_i=0 (i.e. H(z) is FIR), then all θ_i=0 and then this reduces to FIR lossless lattice **!**
- **PS** : If all φ_i=0, then this reduces to Gray-Markel structure **!**

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PS : Can be generalized to 1-input N-output lossless systems (=combine p.22 & p.38 !)