# Dealing with Hamiltonian Structure: Challenges and Successes 

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## Alternating Pencils

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$\square\left(\lambda^{k} A_{k}+\lambda^{k-1} A_{k-1}+\cdots+A_{0}\right) v=0$

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- alternating, even, odd
- Example: anisotropic solids, Lamé equations


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- large, sparse matrices
- compute a few smallest eigenvalues
- symmetry of spectrum


## Spectrum of an Alternating Pencil



## Reduction of Order

# Reduction of Order <br> - (linearization) 

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$$

$$
\lambda\left[\begin{array}{cc}
G & M \\
-M & 0
\end{array}\right]\left[\begin{array}{c}
v \\
w
\end{array}\right]+\left[\begin{array}{cc}
K & 0 \\
0 & M
\end{array}\right]\left[\begin{array}{c}
v \\
w
\end{array}\right]=\left[\begin{array}{l}
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v \\
w
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0
\end{array}\right]
$$

- structure is preserved
- Mackey/Mackey/Mehl/Mehrmann


## Factorization

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$$
\left[\begin{array}{cc}
G & M \\
-M & 0
\end{array}\right]=\left[\begin{array}{cc}
I & 0 \\
\frac{1}{2} G & M
\end{array}\right]^{T}\left[\begin{array}{cc}
0 & I \\
-I & 0
\end{array}\right]\left[\begin{array}{cc}
I & 0 \\
\frac{1}{2} G & M
\end{array}\right]
$$

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\begin{gathered}
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J=\left[\begin{array}{rr}
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\end{gathered}
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\end{array}\right]} \\
J=\left[\begin{array}{rr}
0 & I \\
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\end{array}\right] \\
-N=L^{T} J L \\
-A-\lambda N \Rightarrow J^{T} L^{-T} A L^{-1}-\lambda I
\end{gathered}
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& N=L^{T} J L \\
& -A-\lambda N \quad \Rightarrow \quad J^{T} L^{-T} A L^{-1}-\lambda I \\
& \text { Hamiltonian matrix: } \quad(J H)^{T}=J H
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■ $N=L^{T} J L$
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- Hamiltonian matrix: $\quad(J H)^{T}=J H$

■ Hamiltonian matrix $\Leftrightarrow$ alternating pencil

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$$
\lambda\left[\begin{array}{cc}
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\end{array}\right]\left[\begin{array}{c}
v \\
w
\end{array}\right]+\left[\begin{array}{cc}
K & 0 \\
0 & M
\end{array}\right]\left[\begin{array}{l}
v \\
w
\end{array}\right]=\left[\begin{array}{l}
0 \\
0
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$$

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$$

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-I & 0
\end{array}\right]\left[\begin{array}{cc}
I & 0 \\
\frac{1}{2} G & M
\end{array}\right]} \\
H=J\left[\begin{array}{cc}
I & \frac{1}{2} G \\
0 & I
\end{array}\right]\left[\begin{array}{cc}
K & 0 \\
0 & M^{-1}
\end{array}\right]\left[\begin{array}{cc}
I & 0 \\
-\frac{1}{2} G & I
\end{array}\right]
\end{gathered}
$$

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I & 0 \\
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- Don't form $H$ explicitly.

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H=J\left[\begin{array}{cc}
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-\frac{1}{2} G & I
\end{array}\right]
$$

- Don't form $H$ explicitly.
- Use a Krylov subspace method.

$$
H=J\left[\begin{array}{cc}
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I & 0 \\
-\frac{1}{2} G & I
\end{array}\right]
$$

- Don't form $H$ explicitly.
- Use a Krylov subspace method.
- But we want the smallest eigenvalues.

$$
H=J\left[\begin{array}{cc}
I & \frac{1}{2} G \\
0 & I
\end{array}\right]\left[\begin{array}{cc}
K & 0 \\
0 & M^{-1}
\end{array}\right]\left[\begin{array}{cc}
I & 0 \\
-\frac{1}{2} G & I
\end{array}\right]
$$

- Don't form $H$ explicitly.
- Use a Krylov subspace method.
$\square$ But we want the smallest eigenvalues.

$$
H^{-1}=\left[\begin{array}{cc}
I & 0 \\
\frac{1}{2} G & I
\end{array}\right]\left[\begin{array}{cc}
K^{-1} & 0 \\
0 & M
\end{array}\right]\left[\begin{array}{cc}
I & -\frac{1}{2} G \\
0 & I
\end{array}\right] J^{T}
$$

## LQG Control Problem

# LQG Control Problem <br> $\square \dot{x}=A x+B u$ 

## LQG Control Problem

■ $\dot{x}=A x+B u$
$\square I(x, u)=\int_{0}^{\infty}\left[\frac{1}{2} x^{T} Q x+x^{T} S u+\frac{1}{2} u^{T} R u\right] d t$

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$\square L(x, u, \mu)=I(x, u)+\int_{0}^{\infty} \mu^{T}(\dot{x}-A x-B u) d t$

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$\left[\begin{array}{rrl}0 & I & 0 \\ -I & 0 & 0 \\ 0 & 0 & 0\end{array}\right]\left[\begin{array}{c}\dot{x} \\ \dot{\mu} \\ \dot{u}\end{array}\right]-\left[\begin{array}{ccc}Q & -A^{T} & S \\ -A & 0 & -B \\ S^{T} & -B^{T} & R\end{array}\right]\left[\begin{array}{l}x \\ \mu \\ u\end{array}\right]=0$

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- $L(x, u, \mu)=I(x, u)+\int_{0}^{\infty} \mu^{T}(\dot{x}-A x-B u) d t$
$\left[\begin{array}{rrl}0 & I & 0 \\ -I & 0 & 0 \\ 0 & 0 & 0\end{array}\right]\left[\begin{array}{c}\dot{x} \\ \dot{\mu} \\ \dot{u}\end{array}\right]-\left[\begin{array}{ccc}Q & -A^{T} & S \\ -A & 0 & -B \\ S^{T} & -B^{T} & R\end{array}\right]\left[\begin{array}{l}x \\ \mu \\ u\end{array}\right]=0$
- skew-symmetric/symmetric


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$$
\lambda\left[\begin{array}{rrr}
0 & I & 0 \\
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\end{array}\right]\left[\begin{array}{c}
v \\
w \\
y
\end{array}\right]-\left[\begin{array}{ccc}
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v \\
w \\
y
\end{array}\right]=0
$$

$$
H=\left[\begin{array}{cc}
A-B R^{-1} S^{T} & B R^{-1} B^{T} \\
Q+S R^{-1} S^{T} & -A^{T}+S R^{-1} B^{T}
\end{array}\right]
$$

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$$

- Stable invariant subspace is wanted.


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- complete eigensystem


## Working Directly with the Pencil

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- Schröder (Ph.D. 2008)


## Working Directly with the Pencil

■ Hamiltonian $\Leftrightarrow$ alternating pencil

- $M-\lambda N$
- symplectic $\Leftrightarrow$ palindromic pencil
- $G-\lambda G^{T}$
- Schröder (Ph.D. 2008)
- Kressner/Schröder/Watkins (2008)


## Working with Hamiltonian Matrices

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- symplectic matrix: $\quad S^{T} J S=J$


## Working with Hamiltonian Matrices

- symplectic matrix: $\quad S^{T} J S=J$
- symplectic similarity transformations


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- isotropy and symplectic matrices


## Difficulty Obtaining Hessenberg Form

# Difficulty Obtaining Hessenberg Form <br> - PVL form (1981) 

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- PVL form (1981)
- the desired Hessenberg form


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$■$ PVL form (1981)

- the desired Hessenberg form
- Byers (1983)


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- Ammar/Mehrmann (1991)


## Difficulty Obtaining Hessenberg Form

$■$ PVL form (1981)

- the desired Hessenberg form
- Byers (1983)
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- Ammar/Mehrmann (1991)
- new ideas needed


## Skew-Hamiltonian matrices ...

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## Skew-Hamiltonian matrices ... . . . are easier

- skew-Hamiltonian matrix: $\quad(J K)^{T}=-(J K)$
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- more and bigger invariant subspaces
- Krylov subspaces are automatically isotropic.
- reduction to Hessenberg form
- make use of $H^{2}$


## Symplectic $U R V$ Decomposition

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$■ H=U R_{1} V^{T}=V R_{2} U^{T}$

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- $R_{1}=\left[\begin{array}{cc}S & B \\ 0 & T^{T}\end{array}\right]$ and $R_{2}=\left[\begin{array}{rc}-T & B^{T} \\ 0 & -S^{T}\end{array}\right]$


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- $H^{2}$
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- $H^{2}$
- eigenvalues of $H$
- Benner/Mehrmann/Xu (199X)


## CLM Method

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- $H \leftarrow U^{T} H U$
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- span $\left\{e_{1}\right\}$ invariant under $H^{2}$
$\Rightarrow \operatorname{span}\left\{e_{1}, H e_{1}\right\}$ invariant under $H$


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$\square$ Extract 1-D isotropic invariant subspace.


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$-\operatorname{span}\left\{e_{1}\right\}$ invariant under $H^{2}$
$\Rightarrow \operatorname{span}\left\{e_{1}, H e_{1}\right\}$ invariant under $H$
- Extract 1-D isotropic invariant subspace.
- Build an orthogonal symplectic similarity transformation.


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$\square$ Extract 1-D isotropic invariant subspace.
- Build an orthogonal symplectic similarity transformation.
- Deflate. (many details skipped)


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