
Recent Progress in the Solution of the Hamiltonian Eigenvalue Problem

David S. Watkins

watkins@math.wsu.edu

Department of Mathematics
Washington State University

Alternating Pencils

Alternating Pencils

- $(\lambda^k A_k + \lambda^{k-1} A_{k-1} + \cdots + A_0)v = 0$

Alternating Pencils

- $(\lambda^k A_k + \lambda^{k-1} A_{k-1} + \cdots + A_0)v = 0$
- alternating, even, odd

Alternating Pencils

- $(\lambda^k A_k + \lambda^{k-1} A_{k-1} + \cdots + A_0)v = 0$
- alternating, even, odd
- Example: anisotropic solids, Lamé equations

Alternating Pencils

- $(\lambda^k A_k + \lambda^{k-1} A_{k-1} + \cdots + A_0)v = 0$
- alternating, even, odd
- Example: anisotropic solids, Lamé equations
- $(\lambda^2 M + \lambda G + K)v = 0$

Alternating Pencils

- $(\lambda^k A_k + \lambda^{k-1} A_{k-1} + \cdots + A_0)v = 0$
- alternating, even, odd
- Example: anisotropic solids, Lamé equations
- $(\lambda^2 M + \lambda G + K)v = 0$
- large, sparse matrices

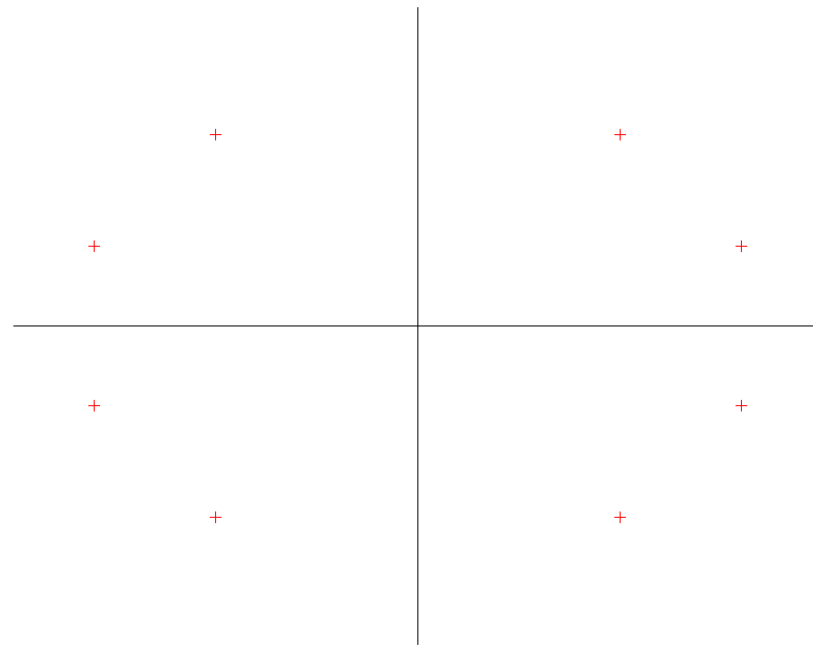
Alternating Pencils

- $(\lambda^k A_k + \lambda^{k-1} A_{k-1} + \cdots + A_0)v = 0$
- alternating, even, odd
- Example: anisotropic solids, Lamé equations
- $(\lambda^2 M + \lambda G + K)v = 0$
- large, sparse matrices
- compute a few smallest eigenvalues

Alternating Pencils

- $(\lambda^k A_k + \lambda^{k-1} A_{k-1} + \cdots + A_0)v = 0$
- alternating, even, odd
- Example: anisotropic solids, Lamé equations
- $(\lambda^2 M + \lambda G + K)v = 0$
- large, sparse matrices
- compute a few smallest eigenvalues
- symmetry of spectrum

Spectrum of an Alternating Pencil



Reduction of Order

Reduction of Order

- (linearization)

Reduction of Order

- (linearization) same as for differential equations

Reduction of Order

- (linearization) same as for differential equations
- $w = \lambda v$,

Reduction of Order

- (linearization) same as for differential equations
- $w = \lambda v, \quad -\lambda Mv + Mw = 0$

Reduction of Order

- (linearization) same as for differential equations
- $w = \lambda v, \quad -\lambda Mv + Mw = 0$



$$\lambda \begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Reduction of Order

- (linearization) same as for differential equations

- $w = \lambda v, \quad -\lambda Mv + Mw = 0$

-

$$\lambda \begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

- structure is preserved

Reduction of Order

- (linearization) same as for differential equations

- $w = \lambda v, \quad -\lambda Mv + Mw = 0$



$$\lambda \begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

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

Factorization

Factorization

$$\begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} = \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}^T \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}$$

Factorization

$$\begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} = \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}^T \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}$$

$$J = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix}$$

Factorization

$$\begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} = \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}^T \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}$$

$$J = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix}$$

- $N = L^T J L$

Factorization

$$\begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} = \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}^T \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}$$

$$J = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix}$$

- $N = L^T J L$

- $A - \lambda N \Rightarrow J^T L^{-T} A L^{-1} - \lambda I$

Factorization

$$\begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} = \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}^T \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}$$

$$J = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix}$$

- $N = L^T J L$
- $A - \lambda N \Rightarrow J^T L^{-T} A L^{-1} - \lambda I$
- *Hamiltonian matrix:* $(JH)^T = JH$

Factorization

$$\begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} = \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}^T \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}$$

$$J = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix}$$

- $N = L^T J L$
- $A - \lambda N \Rightarrow J^T L^{-T} A L^{-1} - \lambda I$
- *Hamiltonian matrix:* $(JH)^T = JH$
- Hamiltonian matrix \Leftrightarrow alternating pencil

Special Case

Special Case

$$\lambda \begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Special Case

$$\lambda \begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} = \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}^T \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}$$

Special Case

$$\lambda \begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & M \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} G & M \\ -M & 0 \end{bmatrix} = \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}^T \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} I & 0 \\ \frac{1}{2}G & M \end{bmatrix}$$

$$H = J \begin{bmatrix} I & \frac{1}{2}G \\ 0 & I \end{bmatrix} \begin{bmatrix} K & 0 \\ 0 & M^{-1} \end{bmatrix} \begin{bmatrix} I & 0 \\ -\frac{1}{2}G & I \end{bmatrix}$$

$$H = J \begin{bmatrix} I & \frac{1}{2}G \\ 0 & I \end{bmatrix} \begin{bmatrix} K & 0 \\ 0 & M^{-1} \end{bmatrix} \begin{bmatrix} I & 0 \\ -\frac{1}{2}G & I \end{bmatrix}$$

$$H = J \begin{bmatrix} I & \frac{1}{2}G \\ 0 & I \end{bmatrix} \begin{bmatrix} K & 0 \\ 0 & M^{-1} \end{bmatrix} \begin{bmatrix} I & 0 \\ -\frac{1}{2}G & I \end{bmatrix}$$

- Don't form H explicitly.

$$H = J \begin{bmatrix} I & \frac{1}{2}G \\ 0 & I \end{bmatrix} \begin{bmatrix} K & 0 \\ 0 & M^{-1} \end{bmatrix} \begin{bmatrix} I & 0 \\ -\frac{1}{2}G & I \end{bmatrix}$$

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

$$H = J \begin{bmatrix} I & \frac{1}{2}G \\ 0 & I \end{bmatrix} \begin{bmatrix} K & 0 \\ 0 & M^{-1} \end{bmatrix} \begin{bmatrix} I & 0 \\ -\frac{1}{2}G & I \end{bmatrix}$$

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

$$H = J \begin{bmatrix} I & \frac{1}{2}G \\ 0 & I \end{bmatrix} \begin{bmatrix} K & 0 \\ 0 & M^{-1} \end{bmatrix} \begin{bmatrix} I & 0 \\ -\frac{1}{2}G & I \end{bmatrix}$$

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

$$H^{-1} = \begin{bmatrix} I & 0 \\ \frac{1}{2}G & I \end{bmatrix} \begin{bmatrix} K^{-1} & 0 \\ 0 & M \end{bmatrix} \begin{bmatrix} I & -\frac{1}{2}G \\ 0 & I \end{bmatrix} J^T$$

LQG Control Problem

LQG Control Problem

- $\dot{x} = Ax + Bu$

LQG Control Problem

- $\dot{x} = Ax + Bu$

- $I(x, u) = \int_0^\infty \left[\frac{1}{2}x^T Qx + x^T Su + \frac{1}{2}u^T Ru \right] dt$

LQG Control Problem

- $\dot{x} = Ax + Bu$
- $I(x, u) = \int_0^\infty \left[\frac{1}{2}x^T Qx + x^T Su + \frac{1}{2}u^T Ru \right] dt$
- $L(x, u, \mu) = I(x, u) + \int_0^\infty \mu^T (\dot{x} - Ax - Bu) dt$

LQG Control Problem

- $\dot{x} = Ax + Bu$

- $I(x, u) = \int_0^\infty \left[\frac{1}{2}x^T Qx + x^T Su + \frac{1}{2}u^T Ru \right] dt$

- $L(x, u, \mu) = I(x, u) + \int_0^\infty \mu^T (\dot{x} - Ax - Bu) dt$

$$\begin{bmatrix} 0 & I & 0 \\ -I & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{\mu} \\ \dot{u} \end{bmatrix} - \begin{bmatrix} Q & -A^T & S \\ -A & 0 & -B \\ S^T & -B^T & R \end{bmatrix} \begin{bmatrix} x \\ \mu \\ u \end{bmatrix} = 0$$

LQG Control Problem

- $\dot{x} = Ax + Bu$

- $I(x, u) = \int_0^\infty \left[\frac{1}{2}x^T Qx + x^T Su + \frac{1}{2}u^T Ru \right] dt$

- $L(x, u, \mu) = I(x, u) + \int_0^\infty \mu^T (\dot{x} - Ax - Bu) dt$

$$\begin{bmatrix} 0 & I & 0 \\ -I & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{\mu} \\ \dot{u} \end{bmatrix} - \begin{bmatrix} Q & -A^T & S \\ -A & 0 & -B \\ S^T & -B^T & R \end{bmatrix} \begin{bmatrix} x \\ \mu \\ u \end{bmatrix} = 0$$

- skew-symmetric/symmetric

Associated eigenvalue problem

Associated eigenvalue problem

$$\lambda \begin{bmatrix} 0 & I & 0 \\ -I & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ w \\ y \end{bmatrix} - \begin{bmatrix} Q & -A^T & S \\ -A & 0 & -B \\ S^T & -B^T & R \end{bmatrix} \begin{bmatrix} v \\ w \\ y \end{bmatrix} = 0$$

Associated eigenvalue problem

$$\lambda \begin{bmatrix} 0 & I & 0 \\ -I & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ w \\ y \end{bmatrix} - \begin{bmatrix} Q & -A^T & S \\ -A & 0 & -B \\ S^T & -B^T & R \end{bmatrix} \begin{bmatrix} v \\ w \\ y \end{bmatrix} = 0$$

$$H = \begin{bmatrix} A - BR^{-1}S^T & BR^{-1}B^T \\ Q + SR^{-1}S^T & -A^T + SR^{-1}B^T \end{bmatrix}$$

Associated eigenvalue problem

$$\lambda \begin{bmatrix} 0 & I & 0 \\ -I & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ w \\ y \end{bmatrix} - \begin{bmatrix} Q & -A^T & S \\ -A & 0 & -B \\ S^T & -B^T & R \end{bmatrix} \begin{bmatrix} v \\ w \\ y \end{bmatrix} = 0$$

$$H = \begin{bmatrix} A - BR^{-1}S^T & BR^{-1}B^T \\ Q + SR^{-1}S^T & -A^T + SR^{-1}B^T \end{bmatrix}$$

- Stable invariant subspace is wanted.

Associated eigenvalue problem

$$\lambda \begin{bmatrix} 0 & I & 0 \\ -I & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v \\ w \\ y \end{bmatrix} - \begin{bmatrix} Q & -A^T & S \\ -A & 0 & -B \\ S^T & -B^T & R \end{bmatrix} \begin{bmatrix} v \\ w \\ y \end{bmatrix} = 0$$

$$H = \begin{bmatrix} A - BR^{-1}S^T & BR^{-1}B^T \\ Q + SR^{-1}S^T & -A^T + SR^{-1}B^T \end{bmatrix}$$

- Stable invariant subspace is wanted.
- complete eigensystem

Working Directly with the Pencil

Working Directly with the Pencil

- Hamiltonian \Leftrightarrow alternating pencil
- $M - \lambda N$

Working Directly with the Pencil

- Hamiltonian \Leftrightarrow alternating pencil
- $M - \lambda N$
- symplectic \Leftrightarrow palindromic pencil
- $G - \lambda G^T$

Working Directly with the Pencil

- Hamiltonian \Leftrightarrow alternating pencil
- $M - \lambda N$
- symplectic \Leftrightarrow palindromic pencil
- $G - \lambda G^T$
- 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

Working with Hamiltonian Matrices

- *symplectic matrix:* $S^T J S = J$

Working with Hamiltonian Matrices

- *symplectic matrix:* $S^T J S = J$
- symplectic similarity transformations

Working with Hamiltonian Matrices

- *symplectic matrix:* $S^T J S = J$
- symplectic similarity transformations
- orthogonal symplectic transformations

Working with Hamiltonian Matrices

- *symplectic matrix:* $S^T J S = J$
- symplectic similarity transformations
- orthogonal symplectic transformations
- *isotropic subspace:* $U^T J U = 0$

Working with Hamiltonian Matrices

- *symplectic matrix*: $S^T J S = J$
- symplectic similarity transformations
- orthogonal symplectic transformations
- *isotropic subspace*: $U^T J U = 0$
- isotropy and symplectic matrices

Difficulty Obtaining Hessenberg Form

Difficulty Obtaining Hessenberg Form

- PVL form (1981)

Difficulty Obtaining Hessenberg Form

- PVL form (1981)
- the desired Hessenberg form

Difficulty Obtaining Hessenberg Form

- PVL form (1981)
- the desired Hessenberg form
- Byers' Hamiltonian QR (1983)

Difficulty Obtaining Hessenberg Form

- PVL form (1981)
- the desired Hessenberg form
- Byers' Hamiltonian QR (1983)
- Van Loan's Curse

Difficulty Obtaining Hessenberg Form

- PVL form (1981)
- the desired Hessenberg form
- Byers' Hamiltonian QR (1983)
- Van Loan's Curse
- getting an isotropic Krylov subspace?

Difficulty Obtaining Hessenberg Form

- PVL form (1981)
- the desired Hessenberg form
- Byers' Hamiltonian QR (1983)
- Van Loan's Curse
- getting an isotropic Krylov subspace?
- Ammar/Mehrmann (1991)

Difficulty Obtaining Hessenberg Form

- PVL form (1981)
- the desired Hessenberg form
- Byers' Hamiltonian QR (1983)
- Van Loan's Curse
- getting an isotropic Krylov subspace?
- Ammar/Mehrmann (1991)
- new ideas needed

Skew-Hamiltonian matrices ...

Skew-Hamiltonian matrices are easier

Skew-Hamiltonian matrices are easier

- *skew-Hamiltonian matrix*: $(JK)^T = -(JK)$

Skew-Hamiltonian matrices are easier

- *skew-Hamiltonian matrix*: $(JK)^T = -(JK)$
- H Hamiltonian $\Rightarrow H^2$ skew Hamiltonian

Skew-Hamiltonian matrices are easier

- *skew-Hamiltonian matrix*: $(JK)^T = -(JK)$
- H Hamiltonian $\Rightarrow H^2$ skew Hamiltonian
- more and bigger invariant subspaces

Skew-Hamiltonian matrices are easier

- *skew-Hamiltonian matrix*: $(JK)^T = -(JK)$
- H Hamiltonian $\Rightarrow H^2$ skew Hamiltonian
- more and bigger invariant subspaces
- Krylov subspaces are automatically isotropic.

Skew-Hamiltonian matrices are easier

- *skew-Hamiltonian matrix*: $(JK)^T = -(JK)$
- H Hamiltonian $\Rightarrow H^2$ skew Hamiltonian
- more and bigger invariant subspaces
- Krylov subspaces are automatically isotropic.
- reduction to Hessenberg form

Skew-Hamiltonian matrices are easier

- *skew-Hamiltonian matrix*: $(JK)^T = -(JK)$
- H Hamiltonian $\Rightarrow H^2$ skew Hamiltonian
- more and bigger invariant subspaces
- Krylov subspaces are automatically isotropic.
- reduction to Hessenberg form
- make use of H^2

Symplectic URV Decomposition

Symplectic URV Decomposition

- $H = UR_1V^T = VR_2U^T$

Symplectic URV Decomposition

- $H = UR_1V^T = VR_2U^T$

- $R_1 = \begin{bmatrix} S & B \\ 0 & T^T \end{bmatrix}$ and $R_2 = \begin{bmatrix} -T & B^T \\ 0 & -S^T \end{bmatrix}$

Symplectic URV Decomposition

- $H = UR_1V^T = VR_2U^T$

- $R_1 = \begin{bmatrix} S & B \\ 0 & T^T \end{bmatrix}$ and $R_2 = \begin{bmatrix} -T & B^T \\ 0 & -S^T \end{bmatrix}$

- $H^2 = U(R_1R_2)U^T$

Symplectic URV Decomposition

- $H = UR_1V^T = VR_2U^T$

- $R_1 = \begin{bmatrix} S & B \\ 0 & T^T \end{bmatrix}$ and $R_2 = \begin{bmatrix} -T & B^T \\ 0 & -S^T \end{bmatrix}$

- $H^2 = U(R_1R_2)U^T$

- $R_1R_2 = \begin{bmatrix} -ST & Z \\ 0 & -(ST)^T \end{bmatrix}$

Symplectic URV Decomposition

- $H = UR_1V^T = VR_2U^T$

- $R_1 = \begin{bmatrix} S & B \\ 0 & T^T \end{bmatrix}$ and $R_2 = \begin{bmatrix} -T & B^T \\ 0 & -S^T \end{bmatrix}$

- $H^2 = U(R_1R_2)U^T$

- $R_1R_2 = \begin{bmatrix} -ST & Z \\ 0 & -(ST)^T \end{bmatrix}$

- eigenvalues of H

Symplectic URV Decomposition

- $H = UR_1V^T = VR_2U^T$
- $R_1 = \begin{bmatrix} S & B \\ 0 & T^T \end{bmatrix}$ and $R_2 = \begin{bmatrix} -T & B^T \\ 0 & -S^T \end{bmatrix}$
- $H^2 = U(R_1R_2)U^T$
- $R_1R_2 = \begin{bmatrix} -ST & Z \\ 0 & -(ST)^T \end{bmatrix}$
- eigenvalues of H
- Benner/Mehrmann/Xu (1998)

CLM Method

CLM Method

- Chu/Liu/Mehrmann (2004)

CLM Method

- Chu/Liu/Mehrmann (2004)
- $H \leftarrow U^T H U$

CLM Method

- Chu/Liu/Mehrmann (2004)

- $H \leftarrow U^T H U$

- $H^2 = \begin{bmatrix} -ST & Z \\ 0 & -(ST)^T \end{bmatrix}$

CLM Method

- Chu/Liu/Mehrmann (2004)

- $H \leftarrow U^T H U$

- $H^2 = \begin{bmatrix} -ST & Z \\ 0 & -(ST)^T \end{bmatrix}$

- $\text{span}\{e_1\}$ invariant under H^2

CLM Method

- Chu/Liu/Mehrmann (2004)

- $H \leftarrow U^T H U$

- $H^2 = \begin{bmatrix} -ST & Z \\ 0 & -(ST)^T \end{bmatrix}$

- $\text{span}\{e_1\}$ invariant under H^2

$\Rightarrow \text{span}\{e_1, H e_1\}$ invariant under H

CLM Method

- Chu/Liu/Mehrmann (2004)
- $H \leftarrow U^T H U$
- $H^2 = \begin{bmatrix} -ST & Z \\ 0 & -(ST)^T \end{bmatrix}$
- $\text{span}\{e_1\}$ invariant under H^2
 $\Rightarrow \text{span}\{e_1, H e_1\}$ invariant under H
- Extract 1-d isotropic invariant subspace.

CLM Method

- Chu/Liu/Mehrmann (2004)
- $H \leftarrow U^T H U$
- $H^2 = \begin{bmatrix} -ST & Z \\ 0 & -(ST)^T \end{bmatrix}$
- $\text{span}\{e_1\}$ invariant under H^2
 $\Rightarrow \text{span}\{e_1, H e_1\}$ invariant under H
- Extract 1-d isotropic invariant subspace.
- Build an orthogonal symplectic similarity transformation.

CLM Method

- Chu/Liu/Mehrmann (2004)
- $H \leftarrow U^T H U$
- $H^2 = \begin{bmatrix} -ST & Z \\ 0 & -(ST)^T \end{bmatrix}$
- $\text{span}\{e_1\}$ invariant under H^2
 $\Rightarrow \text{span}\{e_1, H e_1\}$ invariant under H
- Extract 1-d isotropic invariant subspace.
- Build an orthogonal symplectic similarity transformation.
- Deflate. (with form of H^2 preserved!)

Block CLM Method

Block CLM Method

- CLM works surprisingly well.

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM,

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM, Mehrmann/Schröder/Watkins (2008)

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM, Mehrmann/Schröder/Watkins (2008)
- \mathcal{S} (of dimension k) invariant under H^2

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM, Mehrmann/Schröder/Watkins (2008)
- \mathcal{S} (of dimension k) invariant under H^2
 $\Rightarrow \text{span}\{\mathcal{S}, H\mathcal{S}\}$ invariant under H

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM, Mehrmann/Schröder/Watkins (2008)
- \mathcal{S} (of dimension k) invariant under H^2
 $\Rightarrow \text{span}\{\mathcal{S}, H\mathcal{S}\}$ invariant under H
- Extract k -dimensional isotropic invariant subspace.

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM, Mehrmann/Schröder/Watkins (2008)
- \mathcal{S} (of dimension k) invariant under H^2
 $\Rightarrow \text{span}\{\mathcal{S}, H\mathcal{S}\}$ invariant under H
- Extract k -dimensional isotropic invariant subspace.
- Build a similarity transformation that deflates $2k$ eigenvalues.

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM, Mehrmann/Schröder/Watkins (2008)
- \mathcal{S} (of dimension k) invariant under H^2
 $\Rightarrow \text{span}\{\mathcal{S}, H\mathcal{S}\}$ invariant under H
- Extract k -dimensional isotropic invariant subspace.
- Build a similarity transformation that deflates $2k$ eigenvalues.
- This is

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM, Mehrmann/Schröder/Watkins (2008)
- \mathcal{S} (of dimension k) invariant under H^2
 $\Rightarrow \text{span}\{\mathcal{S}, H\mathcal{S}\}$ invariant under H
- Extract k -dimensional isotropic invariant subspace.
- Build a similarity transformation that deflates $2k$ eigenvalues.
- This is more robust,

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM, Mehrmann/Schröder/Watkins (2008)
- \mathcal{S} (of dimension k) invariant under H^2
 $\Rightarrow \text{span}\{\mathcal{S}, H\mathcal{S}\}$ invariant under H
- Extract k -dimensional isotropic invariant subspace.
- Build a similarity transformation that deflates $2k$ eigenvalues.
- This is more robust, more efficient,

Block CLM Method

- CLM works surprisingly well.
- difficulties with clusters
- Block CLM, Mehrmann/Schröder/Watkins (2008)
- \mathcal{S} (of dimension k) invariant under H^2
 $\Rightarrow \text{span}\{\mathcal{S}, H\mathcal{S}\}$ invariant under H
- Extract k -dimensional isotropic invariant subspace.
- Build a similarity transformation that deflates $2k$ eigenvalues.
- This is more robust, more efficient, but we're still working on it.



















