On the HZ Method for PGEP

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- GEP and PGEP

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hrzz Hrvatska zaklada za znanost

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For such a pair there is a nonsingular matrix F such that

$$F^*AF = \Lambda_A\,, \qquad F^*BF = \Lambda_B,$$

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$$\Lambda_A = \mathrm{diag}(\alpha_1, \ldots, \alpha_n), \qquad \Lambda_B = \mathrm{diag}(\beta_1, \ldots, \beta_n) \succ O.$$

The eigenpairs of (A, B) are: $(\alpha_i/\beta_i, Fe_i)$, $1 \leq i \leq n$; $\quad I_n = [e_1, \ldots, e_n]$.

How to Solve PGEP?

One can try with the transformation $(A, B) \mapsto (L^{-1}AL^{-*}, I)$, $B = LL^*$ and reduce PGEP to EP for one Hermitian matrix.

If L has small singular value(s), then computed $L^{-1}AL^{-*}$ will have corrupt eigenvalues.

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- maximize the minimum eigenvalue of B by rotating the pair

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$$(A, B) \mapsto (A_\varphi, B_\varphi) = (A\cos\varphi + B\sin\varphi, -A\sin\varphi + B\cos\varphi),$$

- or derive a method which works with the initial pair (A, B).

We follow the second path.

Jacobi methods for PGEP

If A and B are real symmetric, we have two diagonalization methods for PGEP:

- Falk-Langemeyer method (shorter: FL method)
  (Elektronische Datenverarbeitung, 1960)
- Hari-Zimmermann variant of the FL method (shorter: HZ method)
  (Hari Ph.D. 1984)

The two methods are connected: the FL method can be viewed as the HZ method with "fast scaled" transformations. So, the FL method seems to be somewhat faster and the HZ method seems to be more robust.

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Numerical tests on large matrices, on parallel machines, have confirmed the advantage of the HZ approach. When implemented as one-sided block algorithm for the GSVD, it is almost perfectly parallelizable, so parallel shared memory versions of the algorithm are highly scalable, and their speedup almost solely depends on the number of cores used.

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So, let us improve that method and take it to public.

Derivation of the Complex HZ Method

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This property of $B^{(0)}$ is maintained during the iteration process:

$$A^{(k+1)} = Z_k^* A^{(k)} Z_k, \qquad B^{(k+1)} = Z_k^* B^{(k)} Z_k, \quad k \geq 0.$$

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$$Z_k = \begin{bmatrix} I & & & & \\ & c_k & & s_k & \\ & & I & & \\ & -\tilde{s}_k & & \tilde{c}_k & \\ & & & & I \end{bmatrix} \begin{matrix} \\ i(k) \\ \\ j(k) \\ \\ \end{matrix}, \qquad i(k) < j(k) \text{ are pivot indices at step } k,$$

$$|c_k|^2 + |s_k|^2 = |\tilde{c}_k|^2 + |\tilde{s}_k|^2 = 1/\sqrt{1 - |b_{i(k)j(k)}|^2} \quad \text{(Hari 1985).}$$

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The selection of pivot pairs $(i(k), j(k))$ defines pivot strategy.

Derivation of the HZ Method

To describe step k, we assume: $A = A^{(k)}$, $A' = A^{(k+1)}$, $Z = Z_k$,

$$\hat{Z} = \begin{bmatrix} c & s \\ -\tilde{s} & \tilde{c} \end{bmatrix}$$ the pivot submatrix of Z.

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We have

$$A' = Z^* A Z, \quad B' = Z^* B Z \qquad \left(\hat{A}' = \hat{Z}^* \hat{A} \hat{Z}, \quad \hat{B}' = \hat{Z}^* \hat{B} \hat{Z}\right).$$

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$\hat{Z}$ is sought in the form of a product of two complex Jacobi rotations and two diagonal matrices.

$\hat{Z}$ is sought in the form:

$$
\begin{array}{ccc}
 & \hat{B} \to \mathrm{diag} & \hat{B} \to I_2 \\
 & \uparrow & \uparrow
\end{array}
$$

$$
\hat{Z} = \begin{bmatrix} \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} e^{\imath \arg(b_{ij})} \\ \frac{\sqrt{2}}{2} e^{-\imath \arg(b_{ij})} & \frac{\sqrt{2}}{2} \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{\sqrt{1+|b_{ij}|}} & 0 \\ 0 & \frac{1}{\sqrt{1-|b_{ij}|}} \end{bmatrix}
$$

$$
\cdot \begin{bmatrix} \cos(\theta + \frac{\pi}{4}) & e^{\imath\alpha} \sin(\theta + \frac{\pi}{4}) \\ -e^{-\imath\alpha} \sin(\theta + \frac{\pi}{4}) & \cos(\theta + \frac{\pi}{4}) \end{bmatrix} \cdot \begin{bmatrix} e^{\imath\omega_i} & 0 \\ 0 & e^{\imath\omega_j} \end{bmatrix}
$$

$$
\begin{array}{cc}
\downarrow & \downarrow \\
\hat{A} \to \mathrm{diag} & \mathrm{diag}(\hat{Z}) \succ O
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$$

Essential Part of the Algorithm

Let

$$b = |b_{ij}|, \quad t = \sqrt{1-b^2}, \quad e = a_{jj} - a_{ii}, \quad \epsilon = \begin{cases} 1, & e \geq 0 \\ -1, & e < 0 \end{cases},$$

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$$\begin{aligned}
u + \imath\, v &= e^{-\imath \arg(b_{ij})}\, a_{ij}, \qquad \tan\gamma = 2\frac{v}{|e|}, \quad -\frac{\pi}{2} < \gamma \leq \frac{\pi}{2} \\
\tan 2\theta &= \epsilon \frac{2u - (a_{ii} + a_{jj})b}{t\sqrt{e^2 + 4v^2}}, \quad -\frac{\pi}{4} < \theta \leq \frac{\pi}{4} \\
2\cos^2\phi &= 1 + b\sin 2\theta + t\cos 2\theta \cos\gamma, \qquad 0 \leq \phi \leq \frac{\pi}{2} \\
2\cos^2\psi &= 1 - b\sin 2\theta + t\cos 2\theta \cos\gamma, \qquad 0 \leq \psi \leq \frac{\pi}{2} \\
e^{\imath\alpha}\sin\phi &= \frac{e^{\imath \arg(b_{ij})}}{2\cos\psi}\left[\sin 2\theta - b - \imath t \cos 2\theta \sin\gamma\right] \\
e^{-\imath\beta}\sin\psi &= \frac{e^{-\imath \arg(b_{ij})}}{2\cos\phi}\left[\sin 2\theta + b + \imath t \cos 2\theta \sin\gamma\right].
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Then

$$\hat{Z} = \frac{1}{\sqrt{1-b^2}} \begin{bmatrix} \cos\phi & e^{\imath\alpha}\sin\phi \\ -e^{-\imath\beta}\sin\psi & \cos\psi \end{bmatrix}$$

Global Convergence

We have used the following measure in the convergence analysis:

$$S(A,B) = \left[S^2(A) + S^2(B)\right]^{\frac{1}{2}}, \quad S^2(A) = \|A - \mathrm{diag}(A)\|_F^2.$$

The HZ method converges globally if

$$A^{(k)} \to \Lambda = \mathrm{diag}(\lambda_1, \ldots, \lambda_n), \quad B^{(k)} \to I_n \qquad \text{as} \quad k \to \infty,$$

holds for any initial pair of Hermitian matrices (A, B) with $B \succ O$.

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We have proved the global convergence for the serial pivot strategies.

We are adapting the proof to hold for a new larger class of generalized serial strategies which includes the known weak wavefront strategies.

Asymptotic Convergence

Let (A, B) have simple eigenvalues:

$$\lambda_1 > \lambda_2 > \cdots > \lambda_n, \qquad \mu = \max\{|\lambda_1|, |\lambda_n|\},$$

$$3\delta_i = \min_{\substack{1\le i\le n \\ j\ne i}} |\lambda_i - \lambda_j|, \quad 1 \le i \le n; \qquad \delta = \min_{1\le i\le n} \delta_i .$$

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Theorem

If $S(B^{(0)}) < \dfrac{1}{n(n-1)}$ *and* $S(A^{(0)}, B^{(0)}) < \dfrac{\delta}{2\sqrt{1+\mu^2}}$,
then for the general cyclic and for the serial strategies it holds, respectively:

$$S(A^{(N)}, B^{(N)}) \leq \sqrt{N(1+\mu^2)}\frac{S^2(A^{(0)}, B^{(0)})}{\delta}, \quad N = n(n-1)/2$$

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In the case of multiple eigenvalues, the method is not quadratically convergent, but can be modified to be such.

THANK YOU. It is hot here, let us cool ourselves down!