Linear Systems With Coefficient Matrices Having Fields of Values Not Containing The Origin *

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This is a continuation of [3] addressing a problem posed by Prof. Kahan. The problem is the following:

> *Given an $n \times n$ (complex) matrix A whose field of values $\mathcal{F}(A)$ does not contain the origin, is it necessary to pivot when solving the linear system $Ax = b$?*

It is well known $\mathcal{F}(A)$ is a compact convex set on the complex plane. Let's draw two projecting lines ℓ_1 and ℓ_2 starting at the origin and "tangent"[1] to the boundary of $\mathcal{F}(A)$ such that $\mathcal{F}(A)$ falls into the smaller section enclosed by ℓ_1 and ℓ_2 as shown in Figure 1. Let α be the angle of the section. Clearly $0 \leq \alpha < \pi$. Set $\theta = \pi - \alpha$. It is proved in [3] that if θ is reasonably

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[1]Here "tangent" may not be the right word since the boundary of $\mathcal{F}(A)$ could not be smooth. So to be more rigous, we could say that ℓ_1 and ℓ_2 are two support lines passing through the origin.

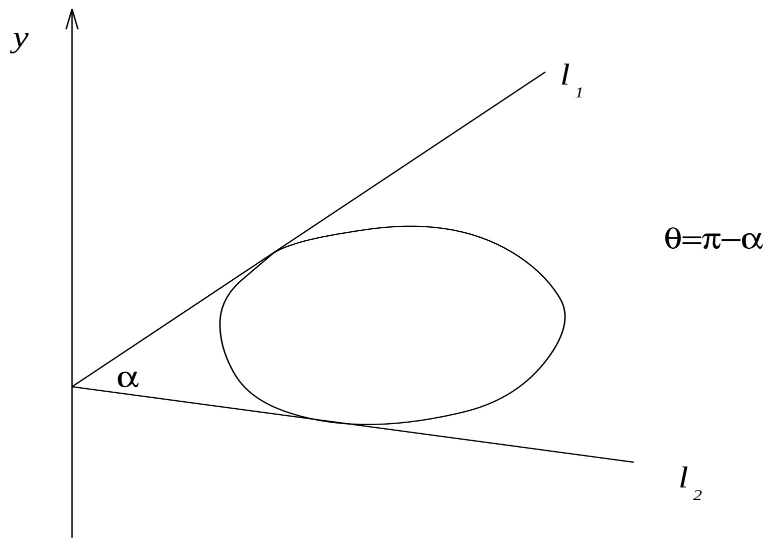

Figure 1: A typical picture.

large, no smaller than 0.1π (say), there is no danger of instability in solving $Ax = b$ without pivoting. However, if θ is rather small, $\theta = \epsilon$ (say), there is a potentiality that elements might grow by a factor $O\left(\frac{1}{\epsilon^3}\right)$. Recently, Ming Gu [2] improves this factor to $O\left(\frac{1}{\epsilon^2}\right)$, which is optimal as far as only order is concerned. This note adopts the idea developed in [1] where the case A being real is studied. We will give a better bound which is *asymptotically attainable.*

It is easy to verify that scalar multiplications do not affect element growth in Gaussian elimination processes. Therefore, without loss of any generality, by rotating the matrix A by an angle β as $e^{i\beta}A$ we can assume that[2] $\mathcal{F}(A)$ lies in the right half plane and the angles between the y-axis and ℓ_1 and between the negative direction of the y-axis and ℓ_2 are equal to $\frac{\theta}{2}$. Set $A = H + iS$, where

$$H = \frac{A + A^*}{2} = H^*,\ S = \frac{A - A^*}{2i} = S^*$$

are both Hermitian, and moreover H is positive definite.

[2]When A is real, $\mathcal{F}(A)$ is symmetric with respect to the x-axis, so either A itself or $-A$ has the desired property.

Doing Gaussian elimination on A, we get a decomposition

$$A = H + iS = LDM^*, \tag{1}$$

where L and M are unit lower triangular matrices, D diagonal. Generally, they are all complex. The existence of the decomposition (1) is guaranteed by the assumption we made on the $\mathcal{F}(A)$ (ref. [3]).

Proposition 1 *Write* $D = \mathrm{diag}\,(d_1, d_2, \cdots, d_n)$. *Then*

$$\Re d_j > 0, \quad j = 1, 2, \cdots, n,$$

where $\Re(\cdot)$ *denotes the real part of a complex number.*

Since $H = H^*$ is positive definite, it has a unique Cholesky decomposition $H = GG^*$, where G is lower triangular. Now (1) gives

$$L^{-1}(H + iS)L^{-*} = DM^*L^{-*} \Rightarrow L^{-1}GG^*L^{-*} + iL^{-1}SL^{-*} = DM^*L^{-*},$$

which yields

$$(G^*L^{-*})^* G^*L^{-*} + iL^{-1}SL^{-*} = DM^*L^{-*}. \tag{2}$$

Let e_j be the jth column of the $n \times n$ identity matrix. Comparing the jth diagonal entries of the two sides of (2) leads to

$$\Re d_j = \|G^*L^{-*}e_j\|_2^2 \tag{3}$$

since M^*L^{-*} is unit upper triangular. Therefore[3]

$$\begin{aligned} \|G^*L^{-*}D^{-1/2}\|_F^2 &= \sum_{j=1}^{n} \|G^*L^{-*}D^{-1/2}e_j\|_2^2 \\ &= \sum_{j=1}^{n} \frac{\|G^*L^{-*}e_j\|_2^2}{|d_j|} \\ &\leq n. \end{aligned} \tag{4}$$

On the other hand,

$$M^{-1}(H + iS)M^{-*} = M^{-1}LD \Rightarrow M^{-1}GG^*M^{-*} + iM^{-1}SM^{-*} = M^{-1}LD,$$

[3] $D^{1/2}$ is not single-valued. But for our purpose it is good enough to pick any one of them and stick to it. $D^{-1/2} \stackrel{\mathrm{def}}{=} (D^{1/2})^{-1}$.

which yields $(G^*M^{-*})^* G^*M^{-*} + iM^{-1}SM^{-*} = M^{-1}LD$, so

$$\Re d_j = \|G^*M^{-*}e_j\|_2^2$$

and

$$\|G^*M^{-*}D^{-1/2}\|_F^2 \le n. \tag{5}$$

It follows from (1) that

$$\begin{aligned} LD^{1/2} &= (GG^* + iS)M^{-*}D^{-1/2} \\ &= (G + iSG^{-*})G^*M^{-*}D^{-1/2}, \\ D^{1/2}M &= D^{-1/2}L^{-1}(GG^* + iS) \\ &= D^{-1/2}L^{-1}G(G^* + iG^{-1}S). \end{aligned}$$

Thus

$$\|LD^{1/2}\|_F \le \sqrt{n}\|G + iSG^{-*}\|_2, \tag{6}$$
$$\|D^{1/2}M\|_F \le \sqrt{n}\|G^* + iG^{-1}S\|_2. \tag{7}$$

Notice that

$$\begin{aligned} \|G + iSG^{-*}\|_2^2 &= \|(G + iSG^{-*})(G^* - iG^{-1}S)\|_2 \\ &= \|GG^* - iS + iS + SG^{-*}G^{-1}S\|_2 \\ &= \|H + SH^{-1}S\|_2 \\ &\le \|H\|_2 + \|SH^{-1}S\|_2, \\ \|G^* + iG^{-1}S\|_2^2 &= \|(G - iSG^{-*})(G^* + iG^{-1}S\|_2 \\ &= \|GG^* + iS - iS + SG^{-*}G^{-1}S\|_2 \\ &= \|H + SH^{-1}S\|_2 \\ &\le \|H\|_2 + \|SH^{-1}S\|_2. \end{aligned}$$

Together with (6) and (7), we have[4]

$$\begin{aligned} \|\,|L|\,|D|\,|M^*|\,\|_F &= \|\,|LD^{1/2}|\,|D^{1/2}M|\,\|_F \\ &\le n\|H + SH^{-1}S\|_2 \\ &\le n(\|H\|_2 + \|SH^{-1}S\|_2). \end{aligned} \tag{8}$$

[4] By $|X|$, we mean its entrywise absolute value, i.e. $|X| \stackrel{\text{def}}{=} (|x_{ij}|)$.

To relate this bound to the angle α, we observe

$$\begin{aligned}\|SH^{-1}S\|_2 &= \|H^{1/2}(H^{-1/2}SH^{-1/2})(H^{-1/2}SH^{-1/2})H^{1/2}\|_2 \\ &\leq \|H^{1/2}\|_2\|H^{-1/2}SH^{-1/2}\|_2^2\|H^{1/2}\|_2 \\ &= \|H\|_2\|H^{-1/2}SH^{-1/2}\|_2^2.\end{aligned}$$

Lemma 1

$$\|H^{-1/2}SH^{-1/2}\|_2 = \max_{x\neq 0}\frac{x^*Sx}{x^*Hx} = \tan\frac{\alpha}{2}.$$

With those in mind, we get

Theorem 1

$$\|\,|L|\,|D|\,|M^*|\,\|_F \leq n\|H\|_2\left[1+\left(\tan\frac{\alpha}{2}\right)^2\right]. \tag{9}$$

Roughly speaking, the bound in [2] is the one obtained by replacing the number inside $[\cdot]$ of (9) with $1+\tan\frac{\alpha}{2}+\frac{3}{2}\left(\tan\frac{\alpha}{2}\right)^2$.

In what follows, we are going to present an example to shown that this inequality is *at least asymptotically attainable* in the sense that there are examples for which the two sides of (9) are arbitrarily close. Consider (ref. [3])

$$A = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}\begin{pmatrix} 1 & 2r \\ 0 & 1 \end{pmatrix}\begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} 1-r & r \\ -r & 1+r \end{pmatrix},$$

where r is positive. It is known the field of values of $\mathcal{F}(A)$ is a disk with center 1 and radius r, i.e.

$$\mathcal{F}(A) = \{z \text{ complex } : |z-1| \leq r\}.$$

So $0 \notin \mathcal{F}(A)$ if $r<1$ (which will be assumed hereafter). For this A, we have

$$\begin{aligned} A = LDM^* &= \begin{pmatrix} 1 & 0 \\ -\frac{r}{1-r} & 1 \end{pmatrix}\begin{pmatrix} 1-r & 0 \\ 0 & \frac{1}{1-r} \end{pmatrix}\begin{pmatrix} 1 & \frac{r}{1-r} \\ 0 & 1 \end{pmatrix}, \\ |L|\,|D|\,|M^*| &= \begin{pmatrix} 1 & 0 \\ \frac{r}{1-r} & 1 \end{pmatrix}\begin{pmatrix} 1-r & 0 \\ 0 & \frac{1}{1-r} \end{pmatrix}\begin{pmatrix} 1 & \frac{r}{1-r} \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1-r & r \\ r & \frac{1+r^2}{1-r} \end{pmatrix}, \\ H &= \frac{A+A^*}{2} = \begin{pmatrix} 1-r & 0 \\ 0 & 1+r \end{pmatrix}, \end{aligned}$$

$$
\begin{aligned}
S &= \frac{A - A^*}{2i} = \begin{pmatrix} 0 & -ri \\ ri & 0 \end{pmatrix}, \\
SH^{-1}S &= \begin{pmatrix} \frac{r^2}{1-r} & 0 \\ 0 & \frac{r^2}{1+r} \end{pmatrix}, \\
\tan\frac{\alpha}{2} &= \frac{r}{\sqrt{1-r^2}}.
\end{aligned}
$$

Hence

$$
\begin{aligned}
\|\,|L|\,|D|\,|M^*|\,\|_F^2 &= (1-r)^2 + 2r^2 + \left(\frac{1+r^2}{1-r}\right)^2 \\
&= \frac{(1-r)^4 + 2r^2(1-r)^2 + (1+r^2)^2}{(1-r)^2}, \\
2\|H\|_2\left[1 + \left(\tan\frac{\alpha}{2}\right)^2\right] &= 2(1+r)\left[1 + \frac{r^2}{1-r^2}\right] = \frac{2}{1-r}, \\
2(\|H\|_2 + \|SH^{-1}S\|_2) &= \frac{2}{1-r}.
\end{aligned}
$$

Define a function $f(r)$ as follows:

$$
\begin{aligned}
f(r) &\stackrel{\mathrm{def}}{=} \frac{\|\,|L|\,|D|\,|M^*|\,\|_F}{2\|H\|_2\left[1 + (\tan\frac{\alpha}{2})^2\right]} \\
&= \frac{1}{2}\sqrt{(1-r)^4 + 2r^2(1-r)^2 + (1+r^2)^2} \\
&= 1 - (1-r) + \frac{3}{4}(1-r)^2 - \frac{1}{4}(1-r)^3 - \frac{1}{32}(1-r)^4 + O((1-r)^5).
\end{aligned}
$$

It is easy to see $f(0) = 1/\sqrt{2} = 0.70710678118655$, $\lim_{r\to 1^-} f(r) = 1 = f(1)$ which shows that the inequalities (8) and (9) are *asymptotically attainable!* And $\min_{0\le r\le 1} f(r) \approx 0.614966762630915$ at

$$
r = \frac{1}{2} - \frac{\sqrt[3]{2/3}}{\sqrt[3]{-9+\sqrt{177}}} + \frac{\sqrt[3]{-9+\sqrt{177}}}{\sqrt[3]{12^2}} \approx 0.273301174242.
$$

To see how fast $f(r)$ approaches 1 pictorially, we refer the reader to Figure 2, where the picture on the left is the graph of $f(r)$ and the one on the right is that of $1 - f(r)$.

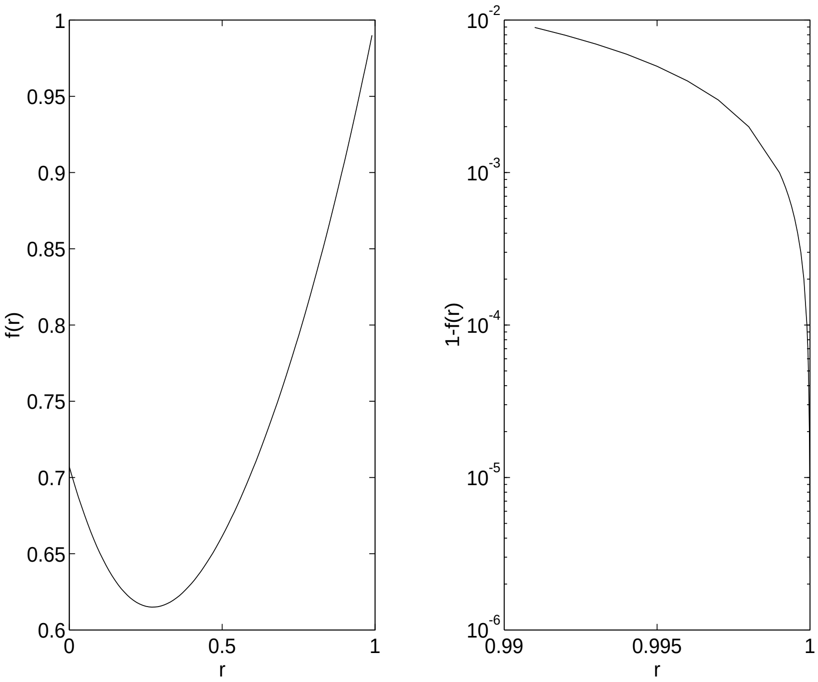

Figure 2: The functions $f(r)$ and $1 - f(r)$.

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[1] G. H. Golub and Ch. van Loan, Unsymmetric positive definite linear systems, *Linear Algebra and its Applications*, **28**(1979), 85–97.

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