

SOLVING SINGULAR GENERALIZED EIGENVALUE PROBLEMS BY A RANK-COMPLETING PERTURBATION*

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Abstract. Generalized eigenvalue problems involving a singular pencil are very challenging to solve, with respect to both accuracy and efficiency. The existing package Guptri is very elegant but may be time-demanding, even for small and medium-sized matrices. We propose a simple method to compute the eigenvalues of singular pencils, based on one perturbation of the original problem of a certain specific rank. For many problems, the method is both fast and robust. This approach may be seen as a welcome alternative to staircase methods.

Key words. singular pencil, singular generalized eigenvalue problem, rank-completing perturbation, Guptri, differential algebraic equations, two-parameter eigenvalue problem, model updating, double eigenvalues, quadratic two-parameter eigenvalue problem

AMS subject classifications. 65F15, 15A18, 15A22, 15A21, 47A55, 65F22

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1. Introduction. We study the computation of eigenvalues of small to medium-sized matrix pencils $A - \lambda B$, where A and B are (real or complex) $n \times m$ matrices such that the matrix pencil $A - \lambda B$ is singular, which means that $m \neq n$, or if $m = n$, then

$$\det(A - \lambda B) \equiv 0.$$

In these cases, the common definition of eigenvalues as roots of $\det(A - \lambda B)$ would only be meaningful for the case $m = n$ but turns out to be useless as any value $\lambda \in \mathbb{C}$ would be an eigenvalue. Therefore, *finite eigenvalues* of a singular matrix pencil $A - \lambda B$ are typically defined as values $\lambda_0 \in \mathbb{C}$ satisfying $\text{rank}(A - \lambda_0 B) < \text{nrnk}(A, B)$, where

$$\text{nrnk}(A, B) := \max_{\zeta \in \mathbb{C}} \text{rank}(A - \zeta B)$$

denotes the *normal rank* of the pencil $A - \lambda B$; see [10]. Similarly, we say that ∞ is an eigenvalue of the singular pencil $A - \lambda B$ if $\text{rank}(B) < \text{nrnk}(A, B)$. In the following we will mainly restrict ourselves to the case $m = n$ as the case $m \neq n$ can easily be reduced to the square case by adding an appropriate number of zero rows or columns.

The singular generalized eigenvalue problem (GEP) is well known to be ill-conditioned as an arbitrarily small perturbation may cause drastic changes in the eigenvalues. A classical example is given by the pencils

$$A - \lambda B = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} - \lambda \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \quad \text{and} \quad \tilde{A} - \lambda \tilde{B} = \begin{bmatrix} 1 & \varepsilon_1 \\ \varepsilon_2 & 0 \end{bmatrix} - \lambda \begin{bmatrix} 1 & \varepsilon_3 \\ \varepsilon_4 & 0 \end{bmatrix},$$

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where $\varepsilon_1, \dots, \varepsilon_4 \in \mathbb{C} \setminus \{0\}$; see [22]. While $A - \lambda B$ is singular and has only the eigenvalue 1, the perturbed pencil $\tilde{A} - \lambda \tilde{B}$ is regular and has the eigenvalues $\frac{\varepsilon_1}{\varepsilon_3}$ and $\frac{\varepsilon_2}{\varepsilon_4}$ that can be anywhere in the complex plane even for tiny absolute values of $\varepsilon_1, \dots, \varepsilon_4$.

On the other hand, it was observed in [43] that a situation as above is exceptional and that generically small perturbations of a singular square pencil make the pencil regular and some of the eigenvalues of the perturbed pencil are very close to the original eigenvalues of the singular pencil. The following example illustrates this.

The MATLAB commands

```
A = diag([1 2 3 0 0 0]);
B = diag([2 3 4 0 0 0]);
eig(U'*A*V, U'*B*V)
```

where U and V are certain random 6×6 orthogonal matrices, compute the following eigenvalues:

```
0.5000 0.6667 0.7500 0.1595 0.6756 0.6543
```

We see that the three (finite) eigenvalues of the regular part are correct. Following the terminology of [40], the other three values are “fake eigenvalues” and correspond to the singular part of the pencil. (Explicit error analysis for the eigenvalues of singular pencils has been undertaken in [9, 11].) Despite this observation, Van Dooren suggests in [40] to solve the singular GEP by first extracting the regular part and then using the QZ algorithm on that part. Wilkinson strongly supports this recommendation in [43].

A robust software package which follows Van Dooren’s approach is Guptri [13, 17]. For a singular pencil, first a “staircase” algorithm is applied to deflate the singular part of the pencil, and then the QZ algorithm is used to compute the eigenvalues of the remaining regular part. While the results of Guptri are usually excellent, this method may be quite time-consuming; for instance, applying Guptri on a singular 300×300 pencil on our machine took over 20 seconds, while MATLAB eig on a random pencil of the same size spent less than a second.¹ Another issue is the fact that staircase type methods such as Guptri need rank decisions. If the pencil has a minimal index of size η (see section 2 for more details), then at least $\eta + 1$ such decisions have to be taken. Typically, these decisions tend to become more and more critical during a run of the staircase algorithm. See, e.g., [14] or [33, Ex. 18], where a variant of the staircase algorithm for the singular two-parameter eigenvalue problem (2EP), introduced in [31], fails in double precision but gets the right result in higher precision.

Another way of extracting the regular part using fewer rank decisions has been suggested in [30]. One may view the singular pencil as a constant coefficient differential-algebraic equation and perform a regularization procedure with the help of a derivative array as described in [3]. In this way, the regular part of the pencil can be extracted by only three nullspace computations. However, the derivative array approach leads to an inflation of the system by a factor of at least $\eta + 1$, where η is the largest minimal index of the given pencil, and may thus result in high computational costs.

We propose a new method to compute the eigenvalues of a singular pencil. The method is based on considering perturbations of rank

$$k = n - \text{nrnk}(A, B),$$

¹We note that this experiment was performed some years ago. A current practical issue is that there is no publicly available 64-bit Guptri code.

which we will call *rank-completing perturbations* as the rank is exactly large enough to generically turn the pencil into a pencil of full normal rank. As we will show, the canonical form of the original regular part of the given pencil stays invariant under generic rank-completing perturbations.

The idea of computing eigenvalues of singular pencils with rank-completing perturbations is not completely new, and the following specific type was used in system theory as early as the 1970s (without the use of the terminology “rank-completing perturbation”). If a linear time-invariant control system of the form

$$\begin{aligned}\dot{x} &= Ax + Bu, \\ y &= Cx + Du\end{aligned}$$

is given, where $A \in \mathbb{R}^{n,n}$, $B \in \mathbb{R}^{n,m}$, $C \in \mathbb{R}^{r,n}$, and $D \in \mathbb{R}^{r,m}$ are the system matrices, x stands for the state of the system, u is the input, and y is the output, then the eigenvalues of the system pencil

$$S(\lambda) = \begin{bmatrix} \lambda I - A & B \\ -C & D \end{bmatrix}$$

are of particular interest in control theory; see [15] and the references therein. (If the system is minimal, then these eigenvalues are also referred to as *transmission zeros* of the system.) Clearly, if $m \neq r$, then the pencil $S(\lambda)$ is rectangular and thus singular. For that case and under the additional assumptions $r < m$ and $\text{nrank } S(\lambda) = n+r$, the following algorithm based on ideas of [6] has been proposed in [24] for the computation of the transmission zeros:

- 1: Select random matrices $[E_1 \ F_1], [E_2 \ F_2] \in \mathbb{R}^{m-r, n+m}$ so that

$$S_i(\lambda) := \begin{bmatrix} \lambda I - A & B \\ -C & D \\ E_i & F_i \end{bmatrix}$$

is regular for $i = 1, 2$.

- 2: Compute the eigenvalues \mathcal{E}_i of $S_i(\lambda)$ for $i = 1, 2$.
- 3: Compute the intersection $\mathcal{E} = \mathcal{E}_1 \cap \mathcal{E}_2$.

Since for each eigenvalue λ_0 of $S(\lambda)$ we have $\text{rank } S_i(\lambda_0) < n+m$, it immediately follows that the eigenvalues of $S(\lambda)$ are contained in the spectrum of $S_i(\lambda)$ for both $i = 1, 2$. The extended matrix pencils will give rise to two sets of fake eigenvalues. As generically these sets will be disjoint if the applied perturbations are generated randomly, it follows that the set \mathcal{E} will generically coincide with the set of eigenvalues of $S(\lambda)$.

However, as pointed out in [15], this method may encounter difficulties in distinguishing the finite zeros from the infinite ones, in particular if the latter occur with a high multiplicity. Another problem may occur in identifying the values that belong to the intersection \mathcal{E} . Although the original eigenvalues of the pencil theoretically coincide with a subset of both \mathcal{E}_1 and \mathcal{E}_2 , they may still differ slightly in practice due to finite precision arithmetic. Therefore, a tolerance has to be prescribed that decides when two values are considered to be equal. If this tolerance is chosen too small, then some of the eigenvalues may be missed. If, on the other hand, the tolerance is set too large, then two close fake eigenvalues of $S_1(\lambda)$ and $S_2(\lambda)$ may be falsely identified as an eigenvalue of $S(\lambda)$.

In this paper, we show that the eigenvalues of a singular pencil can be efficiently computed with the help of *just one* rank-completing perturbation of the form

$$A - \lambda B + \tau U(D_A - \lambda D_B)V^*,$$

where U, V are $n \times k$ matrices with orthonormal columns, D_A, D_B are diagonal $k \times k$ matrices, and τ is a nonzero scalar. The orthonormality of the columns is not strictly necessary but is convenient, for instance, since in this case the norm of the perturbation can easily be controlled by the parameter τ . The problem of identifying the subset of eigenvalues of the original pencil among the computed eigenvalues of the perturbed pencil is then taken care of by the *key observation* that the left and right eigenvectors that correspond to the true eigenvalues satisfy orthogonality relations with respect to the matrices U and V . Thus, instead of comparing the spectra of two different pencils, the true eigenvalues can be separated from the fake eigenvalues by using information from the corresponding left and right eigenvectors from only one perturbed pencil. We note that perturbations of singular matrix pencils have already been considered in [4, 9, 27, 38, 39], but it seems that a detailed investigation of rank-completing perturbations is new, except for [28], where the case of singular Hermitian pencils of normal rank $n - 1$ was considered.

The rest of this paper is organized as follows. After some preliminaries in section 2, we review some motivating applications where one is interested in computing eigenvalues of a singular matrix pencil in section 3. The main theoretical results are presented in section 4, while the numerical method based on these results is introduced in section 5, followed by some numerical experiments in section 6. In section 7 we discuss singular 2EPs and present a new numerical method for such problems. We summarize some conclusions in section 8.

2. Preliminaries. We will interpret matrix pencils either as pairs of matrices $(A, B) \in \mathbb{C}^{n,m} \times \mathbb{C}^{n,m}$ or as $n \times m$ matrix polynomials $A - \lambda B$ of degree at most one and we will switch between these notations whenever useful. An important tool in the theory of singular pencils is the Kronecker canonical form (KCF) of a pencil $A - \lambda B$; see, e.g., [16].

THEOREM 2.1 (Kronecker canonical form). *Let $A - \lambda B$ be a complex $n \times m$ matrix pencil. Then there exist nonsingular matrices $P \in \mathbb{C}^{n,n}$ and $Q \in \mathbb{C}^{m,m}$ such that*

$$(2.1) \quad P(A - \lambda B)Q = \begin{bmatrix} R(\lambda) & 0 \\ 0 & S(\lambda) \end{bmatrix}, \quad R(\lambda) = \begin{bmatrix} J - \lambda I_r & 0 \\ 0 & I_s - \lambda N \end{bmatrix}$$

with J, N in Jordan normal form and in addition N being nilpotent, and

$$S(\lambda) = \text{diag} (L_{m_1}(\lambda), \dots, L_{m_k}(\lambda), L_{n_1}(\lambda)^\top, \dots, L_{n_\ell}(\lambda)^\top),$$

where $L_j(\lambda) = [0 \ I_j] - \lambda [I_j \ 0]$ is of size $j \times (j + 1)$, and $m_i \geq 0$ for $i = 1, \dots, k$, and $n_i \geq 0$ for $i = 1, \dots, \ell$.

The pencils $R(\lambda)$ and $S(\lambda)$ in Theorem 2.1 are called the *regular* and the *singular part* of $A - \lambda B$, respectively. The eigenvalues of J are exactly the finite eigenvalues of $A - \lambda B$, while eigenvalues 0 of N correspond to infinite eigenvalues of $A - \lambda B$. The parameters m_1, \dots, m_k and n_1, \dots, n_ℓ are called the *right* and the *left minimal indices* of $A - \lambda B$, respectively. One may easily check that the normal rank $\text{nrnk}(A, B)$ is equal to $\min(n - \ell, m - k)$. In the remainder of the paper, we will consider square pencils $A - \lambda B$, i.e., we have $n = m$. Note that this implies $k = \ell$, i.e., we must have the same number of right and left minimal indices. However, the particular values of the left and right minimal indices may be distinct.

In contrast to the eigenvalues of singular pencils, the corresponding eigenvectors and deflating subspaces are not well defined. To understand why, we consider the following example borrowed from [29] (and slightly adapted). The pencil

$$(2.2) \quad A - \lambda B = \begin{bmatrix} 1 - \lambda & 0 & 0 \\ 0 & -\lambda & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

obviously has the regular part $R(\lambda) = [1 - \lambda]$ and thus the pencil $A - \lambda B$ has the single eigenvalue $\lambda_0 = 1$ with algebraic multiplicity one. Nevertheless, any vector of the form $x(\alpha, \beta) := [\alpha \ \beta \ \beta]^T$ with $\alpha, \beta \in \mathbb{C}$ satisfies $Ax = \lambda_0 Bx$ and thus could be interpreted as an eigenvector of the pencil. One may argue that the choice $\alpha \neq 0$ and $\beta = 0$ seems to be canonical and gives a unique one-dimensional deflating subspace “corresponding” to the regular part of the pencil. But on the other hand it follows from the equality

$$\begin{bmatrix} 1/\alpha & 0 & 0 \\ -\beta/\alpha & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 - \lambda & 0 & 0 \\ 0 & -\lambda & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \alpha & 0 & 0 \\ \beta & 1 & 0 \\ \beta & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 - \lambda & 0 & 0 \\ 0 & -\lambda & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

that for any choice of α, β with $\alpha \neq 0$, the vector $x(\alpha, \beta)$ can be used to extract the regular part of the pencil as well (and thus could also be considered as “corresponding” to the regular part). For this reason, we restrict ourselves to the computation of eigenvalues of singular pencils but do not consider corresponding eigenvectors. However, as we will see in section 4, the eigenvectors of the *perturbed* pencil play a key role in our approach.

Instead of eigenvectors and deflating subspaces, the concept of *reducing subspaces* introduced in [41] is more adequate in the case of singular pencils. We say that a subspace \mathcal{M} is a *reducing subspace* for the pencil $A - \lambda B$ if $\dim(A\mathcal{M} + B\mathcal{M}) = \dim(\mathcal{M}) - k$, where k is the number of right singular blocks. In the example above, the reducing subspace associated with the eigenvalue $\lambda_0 = 1$ is exactly given by all vectors $x(\alpha, \beta)$ with $\alpha, \beta \in \mathbb{C}$. The *minimal reducing subspace* $\mathcal{M}_{RS}(A, B)$ is the intersection of all reducing subspaces. It is unique and can be numerically computed in a stable way from the generalized upper triangular form (Guptri); see, e.g., [13]. Guptri exists for every pencil $A - \lambda B$ and has the form

$$P^*(A - \lambda B)Q = \begin{bmatrix} A_r - \lambda B_r & \times & \times \\ 0 & A_{\text{reg}} - \lambda B_{\text{reg}} & \times \\ 0 & 0 & A_l - \lambda B_l \end{bmatrix},$$

where the matrices P and Q are unitary, $A_r - \lambda B_r$ has only right singular blocks in its KCF, $A_l - \lambda B_l$ has only left singular blocks in its KCF, and $A_{\text{reg}} - \lambda B_{\text{reg}}$ has only regular blocks in its KCF. We will briefly come back to a minimal reducing subspace in section 3.3.

3. Motivation and applications. Before proposing our new method, we first review some motivating applications where one is interested in computing the eigenvalues of a singular pencil, besides the computation of transmission zeros already mentioned in the introduction.

3.1. Differential algebraic equations and descriptor systems. Linear differential algebraic equations (DAEs) with constant coefficients have the general form

$$E\dot{x} = Ax + f(t), \quad x(t_0) = x_0,$$

where $E, A \in \mathbb{R}^{k,n}$, $t_0 \in \mathbb{R}$, $x_0 \in \mathbb{R}^n$, and $f : [t_0, \infty) \rightarrow \mathbb{R}^k$ is a given inhomogeneity; see [23]. Linear time-invariant descriptor systems consist of a DAE combined with a system input and output and take the form

$$\begin{aligned} E\dot{x} &= Ax + Bu, & x(t_0) &= x_0, \\ y &= Cx + Du, \end{aligned}$$

where, in addition, $B \in \mathbb{R}^{k,m}$, $C \in \mathbb{R}^{p,n}$, $D \in \mathbb{R}^{p,m}$. Here, $x : [t_0, \infty) \rightarrow \mathbb{R}^n$ stands for the state of the descriptor system, $u : [t_0, \infty) \rightarrow \mathbb{R}^m$ is the input, and $y : [t_0, \infty) \rightarrow \mathbb{R}^p$ is the output. As highlighted in [3], the problem may be well-posed even if the underlying pencil $A - \lambda E$ is singular. Indeed, even in the singular case the corresponding DAE may have a solution (even unique) for particular inhomogeneities f and special initial conditions (t_0, x_0) .

3.2. Double eigenvalue problem. Given two $n \times n$ matrices A and B , we are interested in all values λ such that $A + \lambda B$ has a double eigenvalue. For the generic case of a double eigenvalue, we look for independent vectors x and y such that

$$\begin{aligned} (A + \lambda B - \mu I)x &= 0, \\ (A + \lambda B - \mu I)^2 y &= 0, \end{aligned}$$

for some μ . This application is discussed in [33], together with a staircase algorithm to solve it; see also [21]. In the generic case, the problem has $n(n - 1)$ solutions.

In [33], the problem is solved by a linearization of the second equation and followed by the solution of the obtained singular 2EP. The wanted values λ are eigenvalues of the singular pencil $\Delta_1 - \lambda\Delta_0$ of size $3n^2 \times 3n^2$, where

$$\Delta_1 = A \otimes R - I \otimes P, \quad \Delta_0 = B \otimes R - I \otimes Q,$$

for

$$P = \begin{bmatrix} A^2 & AB + BA & -2A \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix}, \quad Q = \begin{bmatrix} 0 & B^2 & -B \\ -I & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad R = \begin{bmatrix} 0 & -B & I \\ 0 & 0 & 0 \\ -I & 0 & 0 \end{bmatrix}.$$

Generically, the pencil $\Delta_1 - \lambda\Delta_0$ will have normal rank $3n^2 - n$. For more details, see [33] as well as [19] for other possible linearizations.

3.3. Singular two-parameter eigenvalue problems. In the singular two-parameter eigenvalue problem we are given a pair of singular pencils $\Delta_1 - \lambda\Delta_0$ and $\Delta_2 - \mu\Delta_0$ (see also (7.2) and (7.3)), and the goal is to find *finite regular eigenvalues* (λ_0, μ_0) , where (see, e.g., [31] for more details)

- λ_0 is a finite eigenvalue of $\Delta_1 - \lambda\Delta_0$,
- μ_0 is a finite eigenvalue of $\Delta_2 - \mu\Delta_0$,
- and there exists a nonzero vector z such that $(\Delta_1 - \lambda_0\Delta_0)z = 0$, $(\Delta_2 - \mu_0\Delta_0)z = 0$, and $z \notin \mathcal{M}_{RS}(\Delta_i, \Delta_0)$ for $i = 1, 2$.

This problem requires more than just solving one singular GEP. We discuss it in more detail in section 7 and present a new numerical method for its solution.

4. Rank-completing perturbations of singular pencils. Let $A - \lambda B$ be a singular pencil, where $A, B \in \mathbb{C}^{n,n}$ and $\text{nrank}(A, B) = n - k$. In this section we investigate the effect of *rank-completing perturbations*, i.e., rank- k generic perturbations of the form

$$(4.1) \quad \tilde{A} - \lambda\tilde{B} := A - \lambda B + \tau (UD_A V^* - \lambda UD_B V^*),$$

where $D_A, D_B \in \mathbb{C}^{k,k}$ are diagonal matrices such that $D_A - \lambda D_B$ is a regular pencil, $U, V \in \mathbb{C}^{n,k}$ have full column rank, and $\tau \in \mathbb{C}$ is nonzero. We investigate the dependence of eigenvalues and eigenvectors of the perturbed pencils on τ .

Above and in the following, the term generic is understood in the following sense. A set $\mathcal{A} \subseteq \mathbb{C}^m$ is called *algebraic* if it is the set of common zeros of finitely many complex polynomials in m variables, and \mathcal{A} is called *proper* if $\mathcal{A} \neq \mathbb{C}^m$. A set $\Omega \subseteq \mathbb{C}^m$ is called *generic* if its complement is contained in a proper algebraic set. In this sense we say that a property \mathcal{P} holds generically with respect to the entries of U and V if there exists a generic set $\Omega \subseteq (\mathbb{C}^{n,k})^2$ (where we interpret $(\mathbb{C}^{n,k})^2$ as \mathbb{C}^{2nk}) such that \mathcal{P} holds for all pencils of the form (4.1) with $(U, V) \in \Omega$.

Remark 4.1. Perturbations of the form (4.1) are not the most general perturbations of rank k . Indeed, completing U and V to nonsingular matrices $P = [U \ \tilde{U}]$ and $Q = [V \ \tilde{V}]$, we obtain that

$$P^{-1}(UD_AV^* - \lambda UD_BV^*)(Q^*)^{-1} = \begin{bmatrix} D_A - \lambda D_B & 0 \\ 0 & 0 \end{bmatrix},$$

which means that the perturbation pencil $UD_AV^* - \lambda UD_BV^*$ has the regular part $D_A - \lambda D_B$ of size $k \times k$, while, generically, a matrix pencil of nrank $k < n$ would have no regular part [8]. Thus, more generally one could consider perturbations of the form

$$(4.2) \quad (A + U_1V_1^* + V_2U_2^*, \ B + U_1W_1^* + W_2U_2^*),$$

where $U_1, V_1, W_1 \in \mathbb{C}^{n,\ell}$ and $U_2, V_2, W_2 \in \mathbb{C}^{n,k-\ell}$ have full column rank for $\ell \in \{0, 1, \dots, k\}$. However, we will restrict ourselves to perturbations of the form (4.1), because of their favorable properties.

Generically, a rank completing perturbation (4.1) of $A - \lambda B$ will result in a regular perturbed pencil $\tilde{A} - \lambda \tilde{B}$. We will show in the following that generically the KCF of $\tilde{A} - \lambda \tilde{B}$ is for all $\tau \neq 0$ given by

$$\begin{bmatrix} R_{\text{reg}}(\lambda) & 0 & 0 \\ 0 & R_{\text{pre}}(\lambda) & 0 \\ 0 & 0 & R_{\text{ran}}(\lambda) \end{bmatrix},$$

where $R_{\text{reg}}(\lambda)$ is the regular part of the original pencil $A - \lambda B$, $R_{\text{pre}}(\lambda) = D_A - \lambda D_B$, and $R_{\text{ran}}(\lambda)$ only has simple eigenvalues that are different from the eigenvalues of $R_{\text{reg}}(\lambda)$ and $R_{\text{pre}}(\lambda)$. Thus, the eigenvalues of $\tilde{A} - \lambda \tilde{B}$ are exactly the (say) p eigenvalues of the original pencil $A - \lambda B$ (counted with multiplicities) and $n - p$ newly generated eigenvalues which consist of k “prescribed” eigenvalues which are the eigenvalues of the perturbation pencil $U(D_A - \lambda D_B)V^*$, and $n - p - k$ “random” eigenvalues that are gathered in the part $R_{\text{ran}}(\lambda)$.

We start by showing that under a rank-completing perturbation, the regular part of $A - \lambda B$ will stay invariant in the above sense. Although our main focus is square pencils, we will state some results in more generality covering also the case of rectangular pencils. The following proposition is a generalization of [28, Thm. 4.2] (which deals with Hermitian pencils) to a block case without any specific structure in A and B .

PROPOSITION 4.2. *Let $A - \lambda B$ be an $n \times m$ singular matrix pencil having at least k left minimal indices, and let $U \in \mathbb{C}^{n,k}$. Then generically (with respect to the entries of U) there exist nonsingular matrices P, Q such that*

$$P(A - \lambda B)Q = \begin{bmatrix} R(\lambda) & 0 \\ 0 & S(\lambda) \end{bmatrix} \quad \text{and} \quad PU = \begin{bmatrix} 0 \\ \tilde{U} \end{bmatrix},$$

where $R(\lambda)$ and $S(\lambda)$ are the regular and singular parts of $A - \lambda B$, respectively, and P is partitioned conformably with $P(A - \lambda B)Q$.

Proof. Without loss of generality we may assume that $A - \lambda B$ is already in the KCF

$$A - \lambda B = \begin{bmatrix} R(\lambda) & 0 \\ 0 & S(\lambda) \end{bmatrix}, \quad R(\lambda) = \begin{bmatrix} J - \lambda I & 0 \\ 0 & I - \lambda N \end{bmatrix},$$

where $S(\lambda)$ is the singular part and $R(\lambda)$ is the regular part of $A - \lambda B$ with J, N in Jordan normal canonical form and, in addition, N nilpotent. Our main strategy is to use the part of P that corresponds to k arbitrarily chosen left minimal indices to introduce zeros in the components of U that correspond to the regular part of $A - \lambda B$. Here, we can treat the components of U corresponding to the “finite eigenvalue part” $J - \lambda I$ and the “infinite eigenvalue part” $I - \lambda N$ separately and we will give the proof only for the first case as the proof for the “infinite eigenvalue part” is completely analogous. Since we will only transform parts of the singular part $S(\lambda)$ that correspond to k arbitrarily chosen left minimal indices and leave all other parts of $S(\lambda)$ unchanged, it is sufficient to assume that $S(\lambda)$ consists of only k singular blocks corresponding to k left minimal indices and that $R(\lambda)$ does not have a part corresponding to infinite eigenvalues. This assumption will simplify the notation considerably.

Thus, we assume that U and $A - \lambda B$ have the forms

$$U = \begin{matrix} r \\ n_1+1 \\ \vdots \\ n_k+1 \end{matrix} \begin{bmatrix} U_0 \\ U_1 \\ \vdots \\ U_k \end{bmatrix} \quad \text{and} \quad A - \lambda B = \begin{matrix} r & n_1 & \dots & n_k \\ n_1+1 & & & \\ \vdots & & & \\ n_k+1 & & & \end{matrix} \begin{bmatrix} J - \lambda I & & & \\ & L_{n_1}(\lambda)^\top & & \\ & & \ddots & \\ & & & L_{n_k}(\lambda)^\top \end{bmatrix}.$$

In the following, we will use the notation $G_\ell = [0 \ I_\ell]^\top$ and $H_\ell = [I_\ell \ 0]^\top$ to write $L_\ell(\lambda)^\top = G_\ell - \lambda H_\ell$ for a singular block corresponding to a left minimal index ℓ . For the transformation matrices P, Q we make the ansatz

$$P = \begin{matrix} r \\ n_1+1 \\ \vdots \\ n_k+1 \end{matrix} \begin{bmatrix} I & P_1 & \dots & P_k \\ & I & & \\ & & \ddots & \\ & & & I \end{bmatrix} \quad \text{and} \quad Q = \begin{matrix} r & n_1 & \dots & n_k \\ n_1 & & & \\ \vdots & & & \\ n_k & & & \end{matrix} \begin{bmatrix} I & -P_1 H_{n_1} & \dots & -P_k H_{n_k} \\ & I & & \\ & & \ddots & \\ & & & I \end{bmatrix}.$$

As P and Q are designed in such a way that B remains unchanged, we get

$$P(A - \lambda B)Q = \begin{bmatrix} J - \lambda I & P_1 G_{n_1} - J P_1 H_{n_1} & \dots & P_k G_{n_k} - J P_k H_{n_k} \\ & L_{n_1}(\lambda)^\top & & \\ & & \ddots & \\ & & & L_{n_k}(\lambda)^\top \end{bmatrix}.$$

It remains to find solutions P_i to the equations $P_i G_{n_i} - J P_i H_{n_i} = 0$ for $i = 1, \dots, k$ to obtain $P(A - \lambda B)Q = A - \lambda B$. Setting $P_i = [p_{i,0} \ p_{i,1} \ \dots \ p_{i,n_i}]$ for $i = 1, \dots, k$, the equations to be solved take the form

$$[p_{i,1} \ \dots \ p_{i,n_i}] = P_i G_{n_i} = J P_i H_{n_i} = [J p_{i,0} \ \dots \ J p_{i,n_i-1}], \quad i = 1, \dots, k.$$

Thus, we may choose $P_i = [p_{i,0} \ J p_{i,0} \ \dots \ J^{n_i} p_{i,0}]$, where $p_{i,0} \in \mathbb{C}^r$ is arbitrary. We will now use the freedom in the choice of $p_{i,0}$ to guarantee that PU has the desired form. To this end, let $u_{i,0}^\top, \dots, u_{i,n_i}^\top \in \mathbb{C}^k$ be the rows of U_i , $i = 1, \dots, k$. Then the first block component of PU is given by $U_0 + P_1 U_1 + \dots + P_k U_k$ and to make it zero, we have to solve the equation

$$(4.3) \quad -U_0 = \sum_{i=1}^k P_i U_i = \sum_{i=1}^k \sum_{j=0}^{n_i} J^j p_{i,0} u_{i,j}^\top$$

for $p_{1,0}, \dots, p_{k,0}$. Using the vec -operation that “vectorizes” a matrix by stacking the columns on top of each other and recalling the well-known identity $\text{vec}(XYZ) = (Z^\top \otimes X) \text{vec}(Y)$ for matrices X, Y, Z , where \otimes denotes the Kronecker product, we obtain that

$$(4.4) \quad -\text{vec}(U_0) = \sum_{i=1}^k \sum_{j=0}^{n_i} (u_{i,j} \otimes J^j) p_{i,0} = M \cdot \begin{bmatrix} p_{1,0} \\ \vdots \\ p_{k,0} \end{bmatrix},$$

where

$$M = \begin{bmatrix} \sum_{j=0}^{n_1} u_{1,j} \otimes J^j & \dots & \sum_{j=0}^{n_k} u_{k,j} \otimes J^j \end{bmatrix} \in \mathbb{C}^{rk, rk}.$$

The determinant of M is a polynomial in the nk entries of U (in fact, it only depends on the entries of U_1, \dots, U_k) which is nonzero for the particular choice $u_{1,0} = e_1, \dots, u_{k,0} = e_k$ and $u_{i,j} = 0$ for $j > 0$, where e_1, \dots, e_k denote the standard basis vectors of \mathbb{C}^k . (Indeed, in this case M is just the identity of size $rk \times rk$.) Thus, generically (with respect to the entries of U), the matrix M is invertible, so equation (4.4) and thus also (4.3) can be uniquely solved for $p_{1,0}, \dots, p_{k,0}$ which finishes the proof. \square

The next result shows that the canonical form of the regular part of the original pencil stays invariant under a generic rank-completing perturbation of the form (4.1). Concerning the eigenvalues of the perturbed pencil that are also eigenvalues of the original singular pencil, the result also states that the corresponding left and right eigenvectors satisfy a particular orthogonality relation.

THEOREM 4.3. *Let $A - \lambda B$ be an $n \times n$ singular pencil of normal rank $n - k$, let $U, V \in \mathbb{C}^{n,k}$ have full column rank, and let $D_A, D_B \in \mathbb{C}^{k,k}$ be such that $D_A - \lambda D_B$ is regular and all eigenvalues of $D_A - \lambda D_B$ are distinct from the eigenvalues of $A - \lambda B$. Then, generically with respect to the entries of U and V^* , the following statements hold for the pencil (4.1):*

- (1) *For each $\tau \neq 0$, there exist nonsingular matrices \tilde{P} and \tilde{Q} such that*

$$(4.5) \quad \tilde{P}(\tilde{A} - \lambda \tilde{B})\tilde{Q} = \begin{bmatrix} R(\lambda) & 0 \\ 0 & R_{\text{new}}(\lambda) \end{bmatrix},$$

where $R(\lambda)$ is the regular part of the original pencil $A - \lambda B$, and $R_{\text{new}}(\lambda)$ is regular and all its eigenvalues are distinct from the eigenvalues of $R(\lambda)$.

- (2) *If λ_0 is a finite eigenvalue of $A - \lambda B$, i.e., $\text{rank}(A - \lambda_0 B) < n - k$, then λ_0 is an eigenvalue of (4.1) for each $\tau \neq 0$. Furthermore, the right null space $\mathcal{N}_r(\lambda_0) := \ker(\tilde{A} - \lambda_0 \tilde{B})$ and the left null space $\mathcal{N}_l(\lambda_0) := \ker((\tilde{A} - \lambda_0 \tilde{B})^*)$ are both constant in $\tau \neq 0$. In addition,*

- (a) $\mathcal{N}_r(\lambda_0) \perp \text{span}(V)$, i.e., if x is a right eigenvector of $\tilde{A} - \lambda\tilde{B}$ associated with λ_0 , then $V^*x = 0$;
 - (b) $\mathcal{N}_l(\lambda_0) \perp \text{span}(U)$, i.e., if y is a left eigenvector of $\tilde{A} - \lambda\tilde{B}$ associated with λ_0 , then $U^*y = 0$.
- (3) If ∞ is a eigenvalue of $A - \lambda B$, i.e., $\text{rank}(B) < n - k$, then ∞ is an eigenvalue of (4.1) for each $\tau \neq 0$. The right and left null spaces $\mathcal{N}_r(\infty) := \ker(\tilde{B})$ and $\mathcal{N}_l(\infty) := \ker(\tilde{B}^*)$ are both constant in $\tau \neq 0$. In addition,
- (a) $\mathcal{N}_r(\infty) \perp \text{span}(V)$, i.e., if x is a right eigenvector of $\tilde{A} - \lambda\tilde{B}$ associated with ∞ , then $V^*x = 0$;
 - (b) $\mathcal{N}_l(\infty) \perp \text{span}(U)$, i.e., if y is a left eigenvector of $\tilde{A} - \lambda\tilde{B}$ associated with ∞ , then $U^*y = 0$.

Proof. First, we will assume that $A - \lambda B$ does not have one of the eigenvalues 0 or ∞ and we will show (1) and (2) for this particular case.

Applying Proposition 4.2, there generically exist nonsingular matrices P, Q such that

$$(4.6) \quad P(A - \lambda B)Q = \begin{bmatrix} R(\lambda) & 0 \\ 0 & S(\lambda) \end{bmatrix}, \quad PU = \begin{bmatrix} 0 \\ U_2 \end{bmatrix}, \quad Q^*V = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix},$$

where $R(\lambda)$ and $S(\lambda)$ are the regular and singular parts of $A - \lambda B$, respectively, both being in KCF, and where U and V are partitioned conformably with $A - \lambda B$. We will now show (1) and (2).

(1) Since $A - \lambda B$ is square and of normal rank $n - k$, it has exactly k left minimal indices, say, n_1, \dots, n_k , and exactly k right minimal indices, say, m_1, \dots, m_k . We may assume without loss of generality that they are paired up to form square blocks of one left and right minimal index each, i.e., we may assume that $S(\lambda)$ has the block diagonal form

$$S(\lambda) = \text{diag} \left(\begin{bmatrix} L_{n_1}(\lambda)^\top & 0 \\ 0 & L_{m_1}(\lambda) \end{bmatrix}, \dots, \begin{bmatrix} L_{n_k}(\lambda)^\top & 0 \\ 0 & L_{m_k}(\lambda) \end{bmatrix} \right).$$

Then the perturbed pencil takes the form

$$P(\tilde{A} - \lambda\tilde{B})Q = \begin{bmatrix} R(\lambda) & 0 \\ \tau U_2(D_A - \lambda D_B)V_1^* & R_{\text{new}}(\lambda) \end{bmatrix},$$

where

$$R_{\text{new}}(\lambda) := S(\lambda) + \tau U_2(D_A - \lambda D_B)V_2^*.$$

Clearly, the determinant of $P(\tilde{A} - \lambda\tilde{B})Q$ is equal to $\det R(\lambda) \cdot \det R_{\text{new}}(\lambda)$ and from the definition of $R_{\text{new}}(\lambda)$ it is clear that the coefficients of $\det R_{\text{new}}(\lambda)$ are polynomials in the entries of U_2 and V_2^* and thus also of U and V^* .

Now let λ_0 be an eigenvalue of $R(\lambda)$, i.e., $\det R(\lambda_0) = 0$. Note that if $e_{j,\ell}$ denotes the j th standard basis vector of \mathbb{C}^ℓ , and $F_i = (\alpha_i - \lambda_0\beta_i)e_{n_i+1, n_i+m_i+1}e_{n_i+1, n_i+m_i+1}^*$, then

$$\det \left(\begin{bmatrix} L_{n_i}(\lambda_0)^\top & 0 \\ 0 & L_{m_i}(\lambda_0) \end{bmatrix} + F_i \right) = (-\lambda_0)^{n_i}(\alpha_i - \lambda_0\beta_i).$$

Thus, with e_j the j th standard basis vector in \mathbb{C}^n , for the particular choice

$$U_2 = V_2 = [e_{n_1+1} \ e_{n_1+m_1+1+n_2+1} \ \dots \ e_{n_1+m_1+1+\dots+n_{k-1}+m_{k-1}+1+n_k+1}]$$

we obtain that

$$\det R_{\text{new}}(\lambda_0) = \tau^k (-\lambda_0)^{n_1+\dots+n_k} (\alpha_1 - \lambda_0\beta_1) \cdots (\alpha_k - \lambda_0\beta_k),$$

which is nonzero as the eigenvalues of $D_A - \lambda D_B$ are by hypothesis distinct from λ_0 . But then $\det R_{\text{new}}(\lambda_0)$ is generically nonzero (the set of all (U, V^*) for which $\det R_{\text{new}}(\lambda_0) = 0$ is by definition an algebraic set, because $\det R_{\text{new}}(\lambda_0)$ is a polynomial in the entries of U and V^*), which shows that $R_{\text{new}}(\lambda_0)$ is generically regular and does not have λ_0 as an eigenvalue. Since intersections of finitely many generic sets are still generic we can conclude that the spectra of $R(\lambda)$ and $R_{\text{new}}(\lambda)$ are disjoint. But then it immediately follows from [25, Lem. 6.11] and [16, XII.2, Thm. 2] that the perturbed pencil $\tilde{A} - \lambda\tilde{B}$ has the KCF as given in (4.5).

(2) Let λ_0 be a eigenvalue of $A - \lambda B$ and thus of $R(\lambda)$. It then follows directly from (1) that λ_0 is also an eigenvalue of $\tilde{A} - \lambda\tilde{B}$ for each $\tau \neq 0$. For the moment, let $\tau \neq 0$ be fixed and let the columns of Y form a basis of the left null space $\mathcal{N}_l(\lambda_0)$ of $\tilde{A} - \lambda\tilde{B}$. Partition

$$Y^* P^{-1} = [Y_1^* \ Y_2^*]$$

conformably with the partition in (4.6). Since λ_0 is not an eigenvalue of $R_{\text{new}}(\lambda)$ we obtain from $Y^*(\tilde{A} - \lambda_0\tilde{B}) = 0$ that $Y_2^* = 0$. But this implies that the columns of Y form a basis for the left null space $\mathcal{N}_l(\lambda_0)$ for all values $\tau \neq 0$ as the construction of the transformation matrices P and Q only depends on A, B , and U , but not on τ . Furthermore, we obtain

$$Y^* U = Y^* P^{-1} P U = [Y_1^* \ 0] \cdot \begin{bmatrix} 0 \\ U_2 \end{bmatrix} = 0,$$

i.e., $\mathcal{N}_l(\lambda_0)$ is orthogonal to the space spanned by the columns of U .

Observe that the statement on the right null space $\mathcal{N}_r(\lambda_0)$ does not follow immediately from the partitioning in (4.6) as in general we have $V_1 \neq 0$. But we can apply the already proved part of the theorem to the pencil $A^* - \lambda B^*$ and the perturbation $V(D_A^* - \lambda D_B^*)U^*$ to obtain the corresponding statements for the right null space $\mathcal{N}_r(\lambda_0)$. This finishes the proof of (2).

Finally, assume that $A - \lambda B$ does have one of the eigenvalues 0 or ∞ . Then apply a Möbius transformation of the form

$$M_{\alpha,\beta}(A - \lambda B) := \alpha A + \beta B - \lambda(\alpha B - \beta A),$$

where $\alpha, \beta \in \mathbb{R}$ are such that $\alpha^2 + \beta^2 = 1$ and such that $M_{\alpha,\beta}(A - \lambda B)$ has neither the eigenvalues 0 nor ∞ . Note that this Möbius transformation just has the effect of “rotating” eigenvalues on the extended real line $\mathbb{R} \cup \{\infty\}$, but it leaves eigenvectors and the Jordan structure invariant; see, e.g., [26]. The result then follows by applying the already proved parts of the theorem on $M_{\alpha,\beta}(A - \lambda B)$ followed by applying the inverse Möbius transformation

$$M_{\alpha,-\beta}(C - \lambda D) := \alpha C - \beta D - \lambda(\alpha D + \beta C)$$

to give the corresponding statements for $A - \lambda B$. In particular, this shows (3). \square

Remark 4.4. We mention that part (1) in Theorem 4.3 is in line with one of the main results of [7], where it was shown that generically the regular part of a singular pencil stays invariant under generic perturbations that do not make the pencil regular. Part (1) of Theorem 4.3 extends this result (in the sense of the theorem) to the

case of rank-completing perturbation. Clearly, the regular part of the pencil will be completely changed if generic perturbations of a rank larger than the difference of the size and the normal rank of the pencil are applied.

Theorem 4.3 characterizes the properties of the eigenvalues from the block R of the perturbed pencil $\tilde{A} - \lambda\tilde{B}$ as in (4.1), i.e., of the eigenvalues that coincide with the eigenvalues of the unperturbed pencil. We will next investigate the properties of the eigenvalues from the newly created block R_{new} . We start with the following lemma that will be needed for the main results. The values $\gamma_1, \dots, \gamma_k$ in the lemma are the eigenvalues that we will prescribe later in Theorem 4.6 using the matrices D_A and D_B .

LEMMA 4.5. *Let $A - \lambda B$ be an $n \times n$ singular pencil of normal rank $n - k$ with left minimal indices n_1, \dots, n_k and right minimal indices m_1, \dots, m_k . Furthermore, let $U, V \in \mathbb{C}^{n,k}$ have full column rank, $N := n_1 + \dots + n_k$, $M := m_1 + \dots + m_k$, and let $\gamma_1, \dots, \gamma_k \in \mathbb{C}$ be given values that are distinct from the eigenvalues of $A - \lambda B$. Then, generically with respect to the entries of U and V^* , the following statements hold:*

- (1) *There exist exactly M pairwise distinct values $\alpha_1, \dots, \alpha_M$ different from the eigenvalues of $A - \lambda B$ and different from $\gamma_1, \dots, \gamma_k$ such that for each α_i there exists a nonzero vector z_i with $(A - \alpha_i B)z_i = 0$ and $V^*z_i = 0$.*
- (2) *There exist exactly N pairwise distinct values β_1, \dots, β_N different from the eigenvalues of $A - \lambda B$ and different from $\gamma_1, \dots, \gamma_k$ and $\alpha_1, \dots, \alpha_M$ such that for each β_i there exists a nonzero vector w_i with $w_i^*(A - \beta_i B) = 0$ and $w_i^*U = 0$.*
- (3) *For any given set of k linearly independent vectors $t_1, \dots, t_k \in \mathbb{C}^k$ there exist nonzero vectors s_1, \dots, s_k with $(A - \gamma_i B)s_i = 0$ and $t_i = V^*s_i$ for $i = 1, \dots, k$.*

Proof. (1) Without loss of generality we may assume that $A - \lambda B$ is in KCF such that the blocks $L_{m_1}(\lambda), \dots, L_{m_k}(\lambda)$ associated with the right minimal indices appear first in the form. Then for each $\alpha \in \mathbb{C}$ different from the eigenvalues of $A - \lambda B$ the columns of

$$\begin{bmatrix} q_{11}(\alpha) & & 0 \\ & \ddots & \\ 0 & & q_{kk}(\alpha) \\ \hline 0 & \dots & 0 \end{bmatrix} \quad \text{with} \quad q_{jj}(\alpha) = \begin{bmatrix} 1 \\ \alpha \\ \vdots \\ \alpha^{m_j} \end{bmatrix}$$

form a basis for $\ker(A - \alpha B)$. (When α is an eigenvalue of $A - \lambda B$, there are additional vectors in $\ker(A - \alpha B)$ since the rank of $A - \alpha B$ drops below the normal rank $n - k$.)

We are looking for $z \neq 0$ and α such that $V^*z = 0$ and $(A - \alpha B)z = 0$. Since we want α to be distinct from the eigenvalues of $A - \lambda B$, the vector z has to be of the form

$$z = c_1 q_1(\alpha) + \dots + c_k q_k(\alpha),$$

where $c = [c_1 \ \dots \ c_k]^T \neq 0$. From $V^*z = 0$ we get the equation

$$(4.7) \quad G(\alpha) c = 0,$$

where $G(\alpha)$ is a $k \times k$ matrix whose element $g_{ij}(\alpha) = v_i^* q_j(\alpha)$ is a polynomial in α which generically with respect to the entries of v_i^* will have degree m_j for $i, j = 1, \dots, k$. Equation (4.7) has a nontrivial solution if and only if $\det G(\alpha) = 0$, where $\det G(\alpha)$ is a polynomial in α which generically with respect to the entries of V^* is of degree M . Thus $\det G(\alpha)$ will have M roots $\alpha_1, \dots, \alpha_M$ (counted with multiplicities).

On the other hand, for each fixed $\mu \in \mathbb{C}$, we have that $\det G(\mu)$ is also a polynomial in the entries of $V^* = [v_1 \ \dots \ v_k]^*$. For the particular choice

$$v_1 = e_1, \quad v_2 = e_{m_1+2}, \quad \dots, \quad v_k = e_{m_1+\dots+m_{k-1}+k}$$

we obtain that $v_i^* q_j(\mu) = \delta_{ij}$ so that $G(\mu) = I_k$ shows that $\det G(\mu)$ is a nonzero polynomial in the entries of V^* . It thus follows that generically with respect to the entries of V^* we will have $\det G(\mu) \neq 0$, and consequently the fixed value μ will generically not be among the roots of $G(\alpha)$ as a polynomial in α . Since the intersection of finitely many generic sets is still generic, it follows that we can generically exclude finitely many values from the zeros $\alpha_1, \dots, \alpha_M$ of $G(\alpha)$. This shows that generically with respect to the entries of V^* , the values $\alpha_1, \dots, \alpha_M$ are different from the eigenvalues of $A - \lambda B$ and also from the given values $\gamma_1, \dots, \gamma_k$.

Next we show that the roots $\alpha_1, \dots, \alpha_M$ of $p(\alpha) := \det G(\alpha)$ generically are pairwise distinct. This is exactly the case if the discriminant $\text{Disc}(p)$ of p is nonzero. Since $\text{Disc}(p)$ is a polynomial in the entries of p (this is well known but can also be seen from the fact that the discriminant is a scalar multiple of the determinant of the Sylvester matrix $S(p, p')$ associated with p and its formal derivative p'), it follows that $\text{Disc}(p)$ is a polynomial with respect to the entries of V^* . It remains to show that $\text{Disc}(p)$ is a nonzero polynomial (because then we will have that $\text{Disc}(p) \neq 0$ is a generic property with respect to the entries of V^*), and for this it is enough to show that for a particular choice of the entries of V we have that the values $\alpha_1, \dots, \alpha_M$ are pairwise distinct. Now taking $v_1 = e_{m_1+1} - \varepsilon_1 e_1$, $v_2 = e_{m_1+m_2+2} - \varepsilon_2 e_{m_1+2}, \dots$, $v_k = e_{m_1+\dots+m_k+k} - \varepsilon_k e_{m_1+\dots+m_{k-1}+k}$, with $\varepsilon_1, \dots, \varepsilon_k > 0$, we obtain that $v_i^* q_j(\alpha) = \delta_{ij} \alpha^{m_j} - \varepsilon_j$ and thus $G(\alpha)$ is diagonal and

$$\det G(\alpha) = (\alpha^{m_1} - \varepsilon_1) \cdots (\alpha^{m_k} - \varepsilon_k).$$

Since the roots of each factor $(\alpha^{m_j} - \varepsilon_j)$ are m_j pairwise distinct complex numbers lying on a circle centered at zero with radius ε_j^{1/m_j} , it remains to choose the values $\varepsilon_1, \dots, \varepsilon_k$ in such a way that the k radii are pairwise distinct to obtain the desired example.

(2) In a way similar to that in (1) we can consider the left null space for $A - \alpha B$ and show the existence of β_1, \dots, β_N and the corresponding nonzero vectors w_1, \dots, w_N , where now the statements are generic with respect to the entries of U . In particular, by interpreting V as already fixed, this shows that generically with respect to the entries of U , the values β_1, \dots, β_N are different not only from the eigenvalues of $A - \lambda B$ and $\gamma_1, \dots, \gamma_k$ but also from the values $\alpha_1, \dots, \alpha_M$ constructed in (1).

(3) With the same notation as in (1) we now aim to solve the equations

$$s_i = c_1 q_1(\gamma_i) + \dots + c_k q_k(\gamma_i) \quad \text{and} \quad V^* s_i = t_i,$$

or, equivalently, $G(\gamma_i)c = t_i$ for $i = 1, \dots, k$. Since γ_i is different from the values $\alpha_1, \dots, \alpha_M$, we have $\det G(\gamma_i) \neq 0$ and hence $G(\gamma_i)c = t_i$ is uniquely solvable for c for $i = 1, \dots, k$. □

The following theorem encapsulates the main result on the new eigenvalues of our perturbed pencil.

THEOREM 4.6. *Let $A - \lambda B$ be an $n \times n$ singular pencil of normal rank $n - k$ with left minimal indices n_1, \dots, n_k and right minimal indices m_1, \dots, m_k . Furthermore, let $U, V \in \mathbb{C}^{n,k}$ have full column rank and let $D_A = \text{diag}(a_1, \dots, a_k), D_B =$*

$\text{diag}(b_1, \dots, b_k) \in \mathbb{C}^{k,k}$ be such that $D_A - \lambda D_B$ is regular and such that all (not necessarily pairwise distinct) values $\gamma_i := \frac{a_i}{b_i}$, $i = 1, \dots, k$, are different from the eigenvalues of $A - \lambda B$. (Here, $\frac{a_i}{b_i}$ is interpreted as the infinite eigenvalue if $b_i = 0$.) Finally, let $N := n_1 + \dots + n_k$ and $M := m_1 + \dots + m_k$. Then generically with respect to the entries of U and V^* , the following statements hold:

- (1) The pencil (4.1) has M simple eigenvalues $\alpha_1, \dots, \alpha_M$ which are independent of $\tau \neq 0$, so that for each of these eigenvalues its right eigenvector x_i is constant in $\tau \neq 0$ (up to scaling) and satisfies $V^*x_i = 0$, while the left eigenvector y_i is a linear function of τ (up to scaling) and satisfies $U^*y_i \neq 0$ for all $\tau \neq 0$.
- (2) The pencil (4.1) has N simple eigenvalues β_1, \dots, β_N which are independent of $\tau \neq 0$, so that for each of these eigenvalues its left eigenvector y_i is constant for $\tau \neq 0$ (up to scaling) and satisfies $U^*y_i = 0$, while the right eigenvector x_i is a linear function of τ (up to scaling) and satisfies $V^*x_i \neq 0$ for all $\tau \neq 0$.
- (3) For each $\tau \neq 0$ each γ_i is an eigenvalue of (4.1) with the same algebraic multiplicity as for the pencil $D_A - \lambda D_B$. Furthermore, the left and right null spaces $\mathcal{N}_l(\gamma_i)$ and $\mathcal{N}_r(\gamma_i)$ of (4.1) associated with γ_i are constant in τ . In addition, we have
 - (a) $\mathcal{N}_r(\gamma_i) \cap \ker(V^*) = \{0\}$, i.e., for each right eigenvector x of (4.1) associated with γ_i we have $V^*x \neq 0$,
 - (b) $\mathcal{N}_l(\gamma_i) \cap \ker(U^*) = \{0\}$, i.e., for each left eigenvector y of (4.1) associated with γ_i we have $U^*y \neq 0$.

(Note that the simplicity of the eigenvalues $\alpha_1, \dots, \alpha_M, \beta_1, \dots, \beta_N$ implies that they are all different from the eigenvalues of $A - \lambda B$ and $\gamma_1, \dots, \gamma_k$.)

Proof. Without loss of generality, we may assume that the infinite eigenvalue is not among the eigenvalues of $D_A - \lambda D_B$. Otherwise, we may as in the proof of Theorem 4.3 apply a Möbius transformation to both $A - \lambda B$ and $D_A - \lambda D_B$ such that $D_A - \lambda D_B$ does not have the eigenvalue ∞ , apply the statement that was proved for this special situation, and finally transform back with the inverse Möbius transformation to obtain the desired result.

Observe that generically with respect to the entries of U and V^* , the statements of Lemma 4.5 hold if we take the eigenvalues of the pencil $D_A - \lambda D_B$ for the values $\gamma_1, \dots, \gamma_k$ and take standard basis vectors e_1, \dots, e_k from \mathbb{C}^k for the vectors t_1, \dots, t_k . We now show (1)–(3).

(1) By Lemma 4.5 there exist exactly M pairwise distinct values $\alpha_1, \dots, \alpha_M$ different from the eigenvalues of $A - \lambda B$ and from $\gamma_1, \dots, \gamma_k$, and nonzero vectors z_1, \dots, z_M such that $(A - \alpha_i B)z_i = 0$ and $V^*z_i = 0$ for $i = 1, \dots, M$. From this we obtain that $(A - \alpha_i B + \tau U D_A V^* - \alpha_i \tau U D_B V^*)z_i = 0$, which means that α_i is an eigenvalue of (4.1) for $\tau \neq 0$ with a right eigenvector z_i that is invariant under τ .

Considering now τ as a variable, it follows that the pencil

$$(4.8) \quad G_i + \tau H_i := (A - \alpha_i B) + \tau U(D_A - \alpha_i D_B)V^*$$

is singular. Suppose that $\text{nrnk}(G_i, H_i) = n - j$ for $j \geq 1$, which means that (4.8) has j right and j left minimal indices. We know from $G_i z_i = 0$ and $H_i z_i = 0$ that one right minimal index is equal to zero. The remaining $j - 1$ right minimal indices are all larger than zero, because otherwise there would exist $y_i \in \ker(G_i) \cap \ker(H_i)$ linearly independent of z_i , which implies that α_i would be a multiple eigenvalue of (4.1) in contradiction to Lemma 4.5.

Now suppose that (4.8) has a left minimal index being zero. Then there exists a vector $w_i \neq 0$ such that $w_i^* G_i = 0$ and $w_i^* H_i = 0$, which implies $w_i^* U = 0$, because V has full rank and $D_A - \alpha_i D_B$ is nonsingular since α_i is different from the eigenvalues of $D_A - \lambda D_B$. But then by Lemma 4.5 α_i is equal to one of the values β_1, \dots, β_N , which is a contradiction. Thus, all left minimal indices of (4.8) are larger than or equal to one.

Furthermore, we know that $\text{rank}(G_i) = n - k$ and $\text{rank}(H_i) = k$ since α_i differs from all finite eigenvalues of $A - \lambda B$ and all eigenvalues of $D_A - \lambda D_B$. It follows that in the KCF of the pencil (4.8) there are at least $n - k - j$ blocks associated with the eigenvalue infinity and at least $k - j$ blocks associated with the eigenvalue zero.

By a simple computation we obtain that the dimension of the KCF of (4.8) is at least $(n + j - 1) \times (n + j - 1)$; therefore the only option is $j = 1$ and hence (4.8) has exactly one right minimal index (being zero) and exactly one left minimal index, say, p . Then another simple computation shows that the dimension of the KCF of (4.8) is at least $(n + p - 1) \times (n + p - 1)$ showing that the left minimal index p must be equal to one. Consequently, there exist linearly independent vectors w_i and z_i such that

$$\begin{aligned} w_i^*(A - \alpha_i B) &= 0, \\ z_i^*(A - \alpha_i B) + w_i^* U(D_A - \alpha_i D_B) V^* &= 0, \\ z_i^* U(D_A - \alpha_i D_B) V^* &= 0 \end{aligned}$$

and $w_i^* U \neq 0$. Up to scaling, the left eigenvector y_i of (4.1) associated with α_i then has the form $y_i(\tau) = w_i + \tau z_i$ and is a linear function of τ .

(2) This follows completely analogously to (1).

(3) Clearly, the standard basis vectors e_1, \dots, e_k are eigenvectors of the pencil $D_A - \lambda D_B$ associated with the eigenvalues $\gamma_1, \dots, \gamma_k$. By Lemma 4.5, there exist k (necessarily linearly independent) vectors $s_1, \dots, s_k \in \mathbb{C}^n$ such that $(A - \gamma_i B)s_i = 0$ and $e_i = V^* s_i$ for $i = 1, \dots, k$. Then we have

$$(\tilde{A} - \gamma_i \tilde{B})s_i = (A - \gamma_i B)s_i + \tau U(D_A - \gamma_i D_B) V^* s_i = 0$$

for each $\tau \neq 0$ for $i = 1, \dots, k$. This implies that the values $\gamma_1, \dots, \gamma_k$ are eigenvalues of $\tilde{A} - \lambda \tilde{B}$ with the same algebraic multiplicities as for $D_A - \lambda D_B$. Furthermore, it follows that the null space $\mathcal{N}_r(\gamma_i)$ does not depend on τ and by construction we have $\mathcal{N}_r(\gamma_i) \cap \ker(V^*) = \{0\}$.

By applying Lemma 4.5 to the pencil $A^* - \lambda B^*$ we obtain the analogous statements for the left null spaces $\mathcal{N}_l(\gamma_i)$. □

SUMMARY 4.7. *Summarizing the results from Theorems 4.3 and 4.6, let $A - \lambda B$ be an $n \times n$ singular pencil of normal rank $n - k$ with left minimal indices n_1, \dots, n_k and right minimal indices m_1, \dots, m_k , and let U, V, D_A, D_B, N , and M be as in Theorem 4.6. Since the regular part of $A - \lambda B$ then has size $r := n - N - M - k$ and we have found $N + M + k$ new eigenvalues in Theorem 4.6, we have classified all eigenvalues of the perturbed pencil*

$$\tilde{A} - \lambda \tilde{B} := A - \lambda B + \tau(UD_A V^* - \lambda UD_B V^*)$$

into the following three groups:

- (1) True eigenvalues: *There are r such eigenvalues that are exactly the eigenvalues of $A - \lambda B$. The corresponding right eigenvectors x and left eigenvectors y satisfy $V^* x = 0$ and $U^* y = 0$.*

- (2) Prescribed eigenvalues: *There are k such eigenvalues that coincide with the k eigenvalues of $D_A - \lambda D_B$. The corresponding right eigenvectors x and left eigenvectors y satisfy both $V^*x \neq 0$ and $U^*y \neq 0$.*
- (3) Random eigenvalues: *These are the remaining $N + M$ eigenvalues. They are simple and if μ is such an eigenvalue with the corresponding right eigenvector x and left eigenvector y , then we either have $V^*x = 0$ and $U^*y \neq 0$ or $V^*x \neq 0$ and $U^*y = 0$.*

Thus, the eigenvalues of $A - \lambda B$ can be identified from the eigenvalues of $\tilde{A} - \lambda \tilde{B}$ by investigating orthogonality properties of the corresponding left and right eigenvectors. We will use this observation in the following section for the development of an algorithm for computing the eigenvalues of a singular square pencil.

Remark 4.8. If A and B are symmetric, then it seems that for our current approach we have to use nonsymmetric rank completing perturbations. Namely, when a symmetric perturbation of the form $\tau U(D_A - \lambda D_B)U^*$ is used, there is an issue with the third group in Summary 4.7 as random eigenvalues appear either as double real eigenvalues or in complex conjugate pairs, and in the former case the orthogonality constraints cannot be satisfied. We leave the study of structured singular pencils for future research.

5. A perturbation method for singular generalized eigenvalue problems. In this section we explain how in the generic case we can extract the finite true eigenvalues numerically even in double precision by solving only one perturbed eigenvalue problem. The key is formed by the existent or nonexistent orthogonality properties of the left and right eigenvectors associated with true, prescribed, and random eigenvalues, respectively.

Let $A - \lambda B$ be a singular $n \times n$ pencil with normal rank $n - k$, where $k > 0$. We determine $\text{nrnk}(A, B)$ by computing $\text{rank}(A - \zeta B)$ for a random ζ . As we have shown in the previous section, if we take two random $n \times k$ matrices U and V with orthonormal columns, a regular $k \times k$ diagonal pencil $D_A - \lambda D_B$, and $\tau \neq 0$, then the perturbed pencil (4.1) is regular. The “true” eigenvalues of $A - \lambda B$ (theoretically) remain constant under this perturbation. In contrast, eigenvalues that originate from the singular part of the pencil (the “random” eigenvalues) may be “anywhere in the complex plane.” In addition, (4.1) also has k “prescribed” eigenvalues that coincide with the eigenvalues of $D_A - \lambda D_B$.

In theory, if we compute all eigenvalues λ_i together with the left and right eigenvectors x_i and y_i for $i = 1, \dots, n$ of (4.1), then $\max(\|V^*x_i\|, \|U^*y_i\|) = 0$ for a true eigenvalue and $\max(\|V^*x_i\|, \|U^*y_i\|) > 0$ for a prescribed or a random eigenvalue, so we can use this criterion to extract the true eigenvalues. In the following we will discuss how the above criterion is affected by computations in finite precision and how it does depend on τ . We will also introduce other criteria that may be used for the same purpose or to further separate true eigenvalues into finite and infinite ones.

If x_i and y_i are normalized left and right eigenvectors of the perturbed problem (4.1) for an eigenvalue λ_i , we can compute the number

$$(5.1) \quad s(\lambda_i) = y_i^* \tilde{B} x_i = y_i^* B x_i + \tau y_i^* U D_B V^* x_i.$$

It is easy to see that $s(\lambda_i) \neq 0$ for a simple finite eigenvalue λ_i . As explained in the following lemma, which is a straightforward generalization of the standard result for a pencil $A - \lambda I$ (see, e.g., [42, sect. 2.9]), $1/|s(\lambda_i)|$ occurs in the expression for a standard condition number of a simple finite eigenvalue.

LEMMA 5.1. *Let λ_i be a simple finite eigenvalue of a regular matrix pencil $\tilde{A} - \lambda\tilde{B}$ and let x_i and y_i be its normalized left and right eigenvectors. If we perturb the pencil into $(\tilde{A} + \theta E) - \lambda(\tilde{B} + \theta F)$ for a small $\theta > 0$, then λ_i perturbs into*

$$(5.2) \quad \lambda_i + \theta \frac{y_i^* E x_i - \lambda_i y_i^* F x_i}{s(\lambda_i)} + \mathcal{O}(\theta^2).$$

If λ_i is a simple finite true eigenvalue, then $V^*x_i = 0$ and $U^*y_i = 0$, which implies that $s(\lambda_i) = y_i^*Bx_i$ does not change with $\tau \neq 0$. For a regular infinite eigenvalue we have $y_i^*B = 0$, $Bx_i = 0$, $V^*x_i = 0$, and $U^*y_i = 0$, therefore $s(\infty) = 0$, again independent of $\tau \neq 0$. On the other hand, we can show that values $s(\lambda)$ of prescribed and random eigenvalues depend on τ and go to 0 as τ goes to 0. For this, we need the following lemma.

LEMMA 5.2. *Let $A - \lambda B$ be a singular pencil and let α be different from all eigenvalues of $A - \lambda B$, i.e., $\text{rank}(A - \alpha B) = \text{nrank}(A, B)$. If $y^*(A - \alpha B) = 0$ and $(A - \alpha B)x = 0$, then $y^*Ax = y^*Bx = 0$.*

Proof. We know from the structure of the left and right singular blocks that $x \in \mathcal{N}_r(\alpha)$ can be written as $x = q_1 + \alpha q_2 + \dots + \alpha^p q_{p+1}$, where the vectors q_1, \dots, q_{p+1} form the chain

$$Aq_1 = 0, Aq_2 = Bq_1, \dots, Aq_{p+1} = Bq_p, Bq_{p+1} = 0$$

for certain $p \geq 0$. Similarly, $y \in \mathcal{N}_l(\alpha)$ can be written as $y = w_1 + \bar{\alpha}w_2 + \dots + \bar{\alpha}^r w_{r+1}$, where the vectors w_1, \dots, w_{r+1} form the chain

$$A^*w_1 = 0, A^*w_2 = B^*w_1, \dots, A^*w_{r+1} = B^*w_r, B^*w_{r+1} = 0$$

for certain $r \geq 0$. To show $y^*Bx = 0$ it is enough to show that $w_i^*Bq_j = 0$ for all $i = 1, \dots, r + 1$ and $j = 1, \dots, p + 1$. For $i = 1$ or $j = p + 1$ this follows from $w_1^*A = 0$ and $Bq_{p+1} = 0$, so we can assume that $i \geq 2$ and $j \leq p$. It follows that $w_i^*Bq_j = w_i^*Aq_{j+1} = w_{i-1}^*Bq_{j+1}$. As we continue in this manner, we eventually reach either $w_1^*A = 0$ or $Bq_{p+1} = 0$. It follows that $y^*Bx = 0$ and from $y^*Ax = \alpha y^*Bx$ we get $y^*Ax = 0$ as well. \square

LEMMA 5.3. *Let λ_i be a prescribed or random eigenvalue of (4.1) under the assumptions of Theorem 4.6, where we assume in addition that all prescribed eigenvalues are algebraically simple. Then there exists a positive constant c_i such that $|s(\lambda_i)| = c_i|\tau|$.*

Proof. First, let λ_i be a prescribed eigenvalue. Then by the proof of Theorem 4.6 the corresponding left and right eigenvectors satisfy $y_i^*(A - \lambda_i B) = 0$ and $(A - \lambda_i B)x_i = 0$, which by Lemma 5.2 implies $y_i^*Bx_i = 0$. But then we have $|s(\lambda_i)| = c_i|\tau|$ with $c_i = |y_i^*UD_BV^*x_i|$ and c_i must be nonzero, because λ_i is a simple eigenvalue of $\tilde{A} - \lambda\tilde{B}$ for $\tau \neq 0$.

Next, let λ_i be a random eigenvalue, such that $V^*x_i = 0$ and $U^*y_i \neq 0$. We know (see the proof of Theorem 4.6) that y_i is a linear function of τ as $y_i(\tau) = w_i + \tau z_i$, where $w_i^*(A - \lambda_i B) = 0$. Since $(A - \lambda_i B)x_i = 0$, it follows from Lemma 5.2 that $w_i^*Bx_i = 0$ and $y_i^*\tilde{B}x_i = y_i^*Bx_i = \bar{\tau}z_i^*Bx_i$. The case $V^*x_i \neq 0$ and $U^*y_i = 0$ can be shown analogously. \square

So, if we take a τ of small absolute value and if all finite true eigenvalues are simple and none of them is too ill-conditioned, then we can separate the finite true eigenvalues from the remaining ones using the values $s(\lambda)$.

TABLE 5.1
Characteristics of the eigenvalues of the perturbed pencil as in (4.1).

Eigenvalue λ	$ s(\lambda) $	$\ V^*x\ $	$\ U^*y\ $
Finite true eigenvalue of $A - \lambda B$	c	$< c\varepsilon/ \tau $	$< c\varepsilon/ \tau $
Infinite true eigenvalue of $A - \lambda B$	$< c\varepsilon$	$< c\varepsilon/ \tau $	$< c\varepsilon/ \tau $
Prescribed eigenvalue of $D_A - \lambda D_B$	$c \tau $	c	c
Random eigenvalue from an L_p block	$c \tau $	$< c\varepsilon/ \tau $	c
Random eigenvalue from an L_p^T block	$c \tau $	c	$< c\varepsilon/ \tau $

Let ε be the machine precision and let the matrices A and B be scaled in such way that $\|A\| = \|B\| = 1$. If all finite true eigenvalues are simple and not too ill-conditioned, then we expect to observe the situation in Table 5.1, where $c > 0$ is a constant, independent of τ , and possibly different for each eigenvalue and each entry in the table.

We now explain the values in Table 5.1. We will start with column $|s(\lambda)|$ and a finite true eigenvalue, where we assume that all finite true eigenvalues are simple and well-conditioned. It follows that λ is a simple eigenvalue of $\tilde{A} - \lambda\tilde{B}$, therefore $y^*\tilde{B}x \neq 0$ and, since this value is independent of τ and ε , we have $|s(\lambda)| = c$. For an infinite eigenvalue we should have $y^*\tilde{B}x = 0$ in exact computation; instead, in finite precision, we get $|y^*\tilde{B}x| < c\varepsilon$. Finally, in the generic case, if λ_i is a prescribed or random eigenvalue, then Lemma 5.3 yields that $|s(\lambda_i)| = c_i|\tau|$ for a positive constant c_i .

Finally, the values in the columns $\|V^*x\|$ and $\|U^*y\|$ that are marked by $< c\varepsilon/|\tau|$ should be zero in exact arithmetic. In finite precision, however, due to the supposed backward stability of the applied eigenproblem solver, the computed eigenvalues and eigenvectors of $\tilde{A} - \lambda\tilde{B}$ are exact eigenpairs of a perturbed pencil $\tilde{A} + E - \lambda(\tilde{B} + F)$, where $\|E\| \leq \tilde{c}_1\|\tilde{A}\|\varepsilon$ and $\|F\| \leq \tilde{c}_2\|\tilde{B}\|\varepsilon$. If we assume that all finite eigenvalues of $\tilde{A} - \lambda\tilde{B}$ are simple, then we have the following result on the first-order eigenvector perturbations. The proof is omitted since it is a straightforward generalization of the result for the pencil $A - \lambda I$ from [42, sect. 2.10].

LEMMA 5.4. *Let all finite eigenvalues λ_i of $\tilde{A} - \lambda\tilde{B}$ be simple and let x_i and y_i be corresponding left and right normalized eigenvectors. If the pencil is perturbed into $\tilde{A} + \theta E - \lambda(\tilde{B} + \theta F)$, then the eigenvector x_i perturbs into*

$$\tilde{x}_i = x_i + \theta \sum_{k=1, k \neq i}^n \frac{y_k^*(E - \lambda_i F)x_i}{(\lambda_i - \lambda_k)s(\lambda_k)} x_k + \mathcal{O}(\theta^2).$$

Let λ_i be a finite true eigenvalue of $A - \lambda B$. Then λ_i is also an eigenvalue of $\tilde{A} - \lambda\tilde{B}$ and $V^*x_i = 0$, where x_i is an exact normalized right eigenvector. In finite precision, x_i becomes perturbed in the directions of other eigenvectors and by Lemma 5.4 a contribution in the direction of another eigenvector depends on the condition number of the corresponding eigenvalue. The only contributions that affect the value of $\|V^*\tilde{x}_i\|$ are those related to prescribed eigenvalues or random eigenvalues from left singular blocks, as right eigenvectors of other eigenvalues are orthogonal to V . As condition numbers of these eigenvalues are equal to $1/(c|\tau|)$ and $\|V^*x_j\| = c$ for the corresponding right eigenvectors, it follows from Lemma 5.4 and the backward stability of the computed eigenpairs that $\|V^*\tilde{x}_i\| < c\varepsilon/|\tau|$.

Next, we discuss appropriate choices for the value τ . If $|\tau|$ is close to ε , then the prescribed and random eigenvalues are very ill-conditioned, and perturbations of eigenvectors may move the values of $\|V^*x_i\|$ and $\|U^*y_i\|$ far away from zero when they should be close to zero. Therefore, if $|\tau|$ is too small, we may not be able to use

Algorithm 1. Computing finite eigenvalues of a singular pencil (A, B) by a rank-completing perturbation.

Input: A and B , perturbation constant τ (default 10^{-2}), thresholds δ_1 (default $\varepsilon^{1/2}$), and δ_2 (default $10^2 \varepsilon$).

Output: Eigenvalues of the finite regular part.

- 1: Scale $A = (1/\alpha)A$ and $B = (1/\beta)B$, where $\alpha = \|A\|_1$ and $\beta = \|B\|_1$.
 - 2: Compute $\text{nrnk}(A, B)$: $k = n - \text{rank}(A - \zeta B)$ for random ζ .
 - 3: Select random $n \times k$ matrices U and V with orthonormal columns.
 - 4: Select diagonal $k \times k$ matrices D_A and D_B such that the eigenvalues of (D_A, D_B) are (likely) different from those of (A, B) (default: choose diagonal elements of D_A and D_B uniformly random from the interval $[1, 2]$).
 - 5: Compute the eigenvalues λ_i , $i = 1, \dots, n$, and right and left eigenvectors x_i and y_i of $(\tilde{A}, \tilde{B}) = (A + \tau U D_A V^*, B + \tau U D_B V^*)$.
 - 6: Compute $s_i = y_i^* \tilde{B} x_i$ for $i = 1, \dots, n$.
 - 7: Compute $\zeta_i = \max(\|V^* x_i\|, \|U^* y_i\|)$ for $i = 1, \dots, n$.
 - 8: Return all eigenvalues $(\alpha/\beta)\lambda_i$, $i = 1, \dots, n$, where $\zeta_i < \delta_1$ and $|s_i| > \delta_2$.
-

the values of $\|V^* x_i\|$ and $\|U^* y_i\|$ to extract the true eigenvalues. Still, if all finite true eigenvalues are simple, then we may use the values $|s(\lambda_i)|$ to extract the finite true eigenvalues.

On the other hand, if $|\tau|$ is large, then all eigenvalues, except the infinite ones, are expected to be well-conditioned, which means that the eigenvectors will not change much and the computed left and right eigenvectors will be orthogonal to V or U in finite precision, when they should be. Therefore, for large $|\tau|$, we can first use $\max(\|V^* x_i\|, \|U^* y_i\|)$ to extract the true eigenvalues and then use $|s(\lambda_i)|$ to distinguish the finite true eigenvalues from the infinite one. In practice, we see this as a better option, because it does not depend on finite true eigenvalues being simple. However, we should not choose $|\tau|$ too large as this may decrease the precision of the computed finite true eigenvalues. Since the computed eigenvalues are, due to assumed backward stability, exact eigenvalues of a slightly perturbed pencil $\tilde{A} - \lambda \tilde{B}$, it is safe to use $|\tau|$ up to $\|\tilde{A}\| \approx \|A\|$ and $\|\tilde{B}\| \approx \|B\|$. Also, since from our analysis it follows that only the absolute value of τ seems to matter, we suggest choosing τ real and positive.

Based on the above discussion, we summarize our method in Algorithm 1. Note that we scale the matrices in such a way that $\|A\|_1 = \|B\|_1 = 1$, mainly for convenience, to determine an appropriate default value for τ .

As we will show by experiments in the next section, the above approach seems to work very well in double precision for small or moderate singular pencils. Of course, if some of the eigenvalues are very ill-conditioned (for instance, when some of the eigenvalues are multiple), then the method may fail in extracting some of the finite true eigenvalues. However, its advantage over staircase-based methods may be the following observation: if we make a wrong rank decision in a staircase algorithm, then the method usually fails completely and returns no eigenvalues at all; see Example 6.4 in the next section. In contrast, the method proposed here is able to detect, if not all, then at least the well-conditioned finite eigenvalues of the pencil under consideration.

6. Numerical examples. In this section we demonstrate the method with several numerical examples computed in MATLAB 2015b. All numerical examples and implementations of the algorithms are available in [35].

Example 6.1. We take a 7×7 pencil $A - \lambda B$, where

$$A = \begin{bmatrix} -1 & -1 & -1 & -1 & -1 & -1 & -1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 2 & 1 & 1 & 1 & 1 & 1 \\ 1 & 2 & 3 & 3 & 3 & 3 & 3 \\ 1 & 2 & 3 & 2 & 2 & 2 & 2 \\ 1 & 2 & 3 & 4 & 3 & 3 & 3 \\ 1 & 2 & 3 & 4 & 5 & 5 & 4 \end{bmatrix}, \quad B = \begin{bmatrix} -2 & -2 & -2 & -2 & -2 & -2 & -2 \\ 2 & -1 & -1 & -1 & -1 & -1 & -1 \\ 2 & 5 & 5 & 5 & 5 & 5 & 5 \\ 2 & 5 & 5 & 4 & 4 & 4 & 4 \\ 2 & 5 & 5 & 6 & 5 & 5 & 5 \\ 2 & 5 & 5 & 6 & 7 & 7 & 7 \\ 2 & 5 & 5 & 6 & 7 & 6 & 6 \end{bmatrix}.$$

The matrices are built in such a way that the KCF of the pencil contains blocks of all four possible types, $\text{nrank}(A, B) = 6$, and the pencil is singular. Its KCF has blocks $J_1(1/2)$, $J_1(1/3)$, N_1 , L_1 , and L_2^T . If we apply Algorithm 1, we get the values in the following table. Note that values λ_k in the first column are values from line 8 of Algorithm 1, which are scaled back to match the eigenvalues of the original matrix pencil $A - \lambda B$ whose matrices are scaled in line 1 since they do not satisfy $\|A\|_1 = \|B\|_1 = 1$.

k	λ_k	$ s_k $	$\ V^*x_k\ $	$\ U^*y_k\ $
1	0.333333	$1.5 \cdot 10^{-2}$	$1.3 \cdot 10^{-15}$	$1.3 \cdot 10^{-14}$
2	0.500000	$9.5 \cdot 10^{-4}$	$1.3 \cdot 10^{-14}$	$1.9 \cdot 10^{-14}$
3	∞	$3.8 \cdot 10^{-19}$	$2.8 \cdot 10^{-15}$	$1.3 \cdot 10^{-14}$
4	$-0.244794 + 0.421723i$	$7.8 \cdot 10^{-3}$	$5.8 \cdot 10^{-2}$	$5.6 \cdot 10^{-15}$
5	$-0.244794 - 0.421723i$	$7.8 \cdot 10^{-3}$	$5.8 \cdot 10^{-2}$	$5.6 \cdot 10^{-15}$
6	0.383682	$2.1 \cdot 10^{-4}$	$2.6 \cdot 10^{-2}$	$4.2 \cdot 10^{-1}$
7	0.478292	$2.6 \cdot 10^{-4}$	$9.2 \cdot 10^{-15}$	$5.2 \cdot 10^{-1}$

The values in the table follow the pattern from the previous section and it is easy to detect that λ_1 and λ_2 are finite true eigenvalues, λ_3 is a true infinite eigenvalue, λ_4, λ_5 , and λ_7 are random eigenvalues, and λ_6 is the prescribed eigenvalue.

Example 6.2. We take example C3 from [12] that comes from control theory and belongs to a set of examples C1, C2, and C3, where each has successively more ill-conditioned eigenvalues. The pencil has the form

$$A - \lambda B = \begin{bmatrix} 1 & -2 & 100 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & -75 \\ 0 & 0 & 0 & 0 & 2 \end{bmatrix} - \lambda \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

Its KCF contains blocks L_2 , $J_1(1)$, and $J_1(2)$. As the pencil is rectangular, we add a zero line to make it square. This adds an L_0^T block to the KCF. Algorithm 1 returns the following table for $A - \lambda B$, from which the finite true eigenvalues 1 and 2 can be extracted.

k	λ_k	$ s_k $	$\ V^*x_k\ $	$\ U^*y_k\ $
1	1.000000	$1.2 \cdot 10^{-2}$	$1.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-15}$
2	2.000000	$1.2 \cdot 10^{-2}$	$2.3 \cdot 10^{-15}$	$1.7 \cdot 10^{-15}$
3	$-0.693767 + 1.563033i$	$2.1 \cdot 10^{-2}$	$2.3 \cdot 10^{-15}$	$5.0 \cdot 10^{-1}$
4	$-0.693767 - 1.563033i$	$2.1 \cdot 10^{-2}$	$2.3 \cdot 10^{-15}$	$5.0 \cdot 10^{-1}$
5	78.673901	$2.8 \cdot 10^{-3}$	$3.3 \cdot 10^{-1}$	$6.4 \cdot 10^{-1}$

As in [12] we add some noise and perturb initial $A - \lambda B$ into $\hat{A} - \lambda \hat{B}$ by adding $10^{-6} \text{rand}(4, 5)$ to A and B . True eigenvalues of $\hat{A} - \lambda \hat{B}$ can still be extracted by Algorithm 1 if we adjust the parameter δ_1 . The values we get are in the following table:

k	λ_k	$ s_k $	$\ V^*x_k\ $	$\ U^*y_k\ $
1	0.999990	$7.6 \cdot 10^{-3}$	$2.6 \cdot 10^{-15}$	$5.2 \cdot 10^{-7}$
2	2.000058	$7.6 \cdot 10^{-3}$	$2.8 \cdot 10^{-15}$	$5.6 \cdot 10^{-7}$
3	101.850555	$8.2 \cdot 10^{-4}$	$1.3 \cdot 10^{-1}$	$3.7 \cdot 10^{-1}$
4	-14.308508	$1.9 \cdot 10^{-2}$	$5.8 \cdot 10^{-16}$	$4.5 \cdot 10^{-1}$
5	15.734162	$9.3 \cdot 10^{-3}$	$1.0 \cdot 10^{-17}$	$4.7 \cdot 10^{-1}$

Example 6.3. This is an example from [14, sect. 5], where the staircase algorithm fails to find a regular subspace of proper size under a small random perturbation. We take

$$A_1 - \lambda B_1 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} - \lambda \begin{bmatrix} \delta & 0 & 0 & 0 \\ 0 & \delta & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

where $\delta = 1.5 \cdot 10^{-8}$. The KCF structure of the pencil is $J_2(0)$ and L_1 , which means that 0 is a double eigenvalue. It is reported in [14] that if we add a random perturbation of size 10^{-14} to the pencil, then Guptri reports the regular part $J_1(0)$ and we have been able to confirm this using a MATLAB implementation of Guptri in [34]. If we enlarge the perturbation to 10^{-11} , Guptri returns no regular part at all, while Algorithm 1 returns two finite true eigenvalues λ_1 and λ_2 from the following table:

k	λ_k	$ s_k $	$\ V^*x_k\ $	$\ U^*y_k\ $
1	$-1.4306543 \cdot 10^{-3}$	$1.6 \cdot 10^{-11}$	$5.5 \cdot 10^{-17}$	$6.7 \cdot 10^{-10}$
2	$9.9599790 \cdot 10^{-4}$	$1.6 \cdot 10^{-11}$	0.0	$6.7 \cdot 10^{-10}$
3	$-2.2641370 \cdot 10^7$	$5.2 \cdot 10^{-9}$	$2.9 \cdot 10^{-18}$	$2.6 \cdot 10^{-6}$
4	$1.1878888 \cdot 10^0$	$1.6 \cdot 10^{-3}$	$2.0 \cdot 10^{-1}$	$7.8 \cdot 10^{-1}$

Example 6.4. We take the singular pencil $\Delta_1 - \lambda \Delta_0$ of size 300×300 from [33, Ex. 18]. This example is related to two random matrices A and B of size 10×10 in a way that the true eigenvalues of $\Delta_1 - \lambda \Delta_0$ are exactly the values λ such that $A + \lambda B$ has a multiple eigenvalue (see section 3.2). We know from the properties of the problem that there are 90 such values λ and that the KCF of $\Delta_1 - \lambda \Delta_0$ contains 100 N_1 and 10 left and 10 right singular blocks. The conjecture from [33] is that the singular blocks are 5 L_4^T , 5 L_5^T , 5 L_5 , and 5 L_6 blocks.

This example is also available as `demo_double_eig_mp` in toolbox MultiParEig [35]. The staircase algorithm in MultiParEig fails to extract the finite regular part of size 90 in double precision but manages to extract all 90 finite true eigenvalues using quadruple precision and the Multiprecision Computing Toolbox [36]. If we apply Algorithm 1 to $\Delta_1 - \lambda \Delta_0$ in double precision, we get the following values:

k	λ_k	$ s_k $	$\ V^*x_k\ $	$\ U^*y_k\ $
1	$0.508999 + 2.016378i$	$3.0 \cdot 10^{-3}$	$2.3 \cdot 10^{-14}$	$1.6 \cdot 10^{-14}$
\vdots	\vdots	\vdots	\vdots	\vdots
89	$4.266290 - 0.925962i$	$1.4 \cdot 10^{-6}$	$2.6 \cdot 10^{-13}$	$7.2 \cdot 10^{-14}$
90	-0.628208	$3.2 \cdot 10^{-7}$	$2.8 \cdot 10^{-14}$	$1.3 \cdot 10^{-11}$
91	∞	$1.1 \cdot 10^{-17}$	$7.1 \cdot 10^{-15}$	$7.1 \cdot 10^{-15}$
\vdots	\vdots	\vdots	\vdots	\vdots
190	∞	$2.8 \cdot 10^{-21}$	$5.9 \cdot 10^{-15}$	$7.9 \cdot 10^{-15}$
191	-6.276934	$3.2 \cdot 10^{-7}$	$2.7 \cdot 10^{-14}$	$4.5 \cdot 10^{-5}$
\vdots	\vdots	\vdots	\vdots	\vdots
300	7.125982	$2.3 \cdot 10^{-5}$	$1.7 \cdot 10^{-1}$	$1.0 \cdot 10^{-2}$

From the columns $\|V^*x_k\|$ and $\|U^*y_k\|$ we get $\max_{k=1,\dots,190}(\max(\|V^*x_k\|, \|U^*y_k\|)) = 1.3 \cdot 10^{-11}$ and $\min_{k=191,\dots,300} \max(\|V^*x_k\|, \|U^*y_k\|) = 4.5 \cdot 10^{-5}$, which shows a clear

gap which separates true eigenvalues from the prescribed and random ones. Next, in the set of true eigenvalues there is also a clear gap between s_{90} and s_{91} which separates finite true eigenvalues from infinite ones, since $\min_{k=1,\dots,90} |s_k| = 3.2 \cdot 10^{-7}$ and $\max_{k=91,\dots,190} |s_k| = 1.1 \cdot 10^{-17}$.

7. The singular two-parameter eigenvalue problem. We now expand on section 3.3. In a 2EP [1] we have the equations

$$(7.1) \quad \begin{aligned} (A_1 + \lambda B_1 + \mu C_1) x_1 &= 0, \\ (A_2 + \lambda B_2 + \mu C_2) x_2 &= 0, \end{aligned}$$

where A_1 , B_1 , and C_1 are of size $n_1 \times n_1$, and A_2 , B_2 , and C_2 are of size $n_2 \times n_2$. Sought are scalars λ, μ and nonzero vectors x_1 and x_2 such that (7.1) is satisfied. We say that (λ, μ) is an eigenvalue of the 2EP and the tensor product $x_1 \otimes x_2$ is the corresponding eigenvector. Define the operator determinants

$$(7.2) \quad \begin{aligned} \Delta_0 &= B_1 \otimes C_2 - C_1 \otimes B_2, \\ \Delta_1 &= C_1 \otimes A_2 - A_1 \otimes C_2, \\ \Delta_2 &= A_1 \otimes B_2 - B_1 \otimes A_2. \end{aligned}$$

Then problem (7.1) is related to a coupled pair of GEPs,

$$(7.3) \quad \begin{aligned} \Delta_1 z &= \lambda \Delta_0 z, \\ \Delta_2 z &= \mu \Delta_0 z \end{aligned}$$

for a decomposable tensor $z = x_1 \otimes x_2$. If Δ_0 is nonsingular, then Atkinson [1] shows that the solutions of (7.1) and (7.3) agree and the matrices $\Delta_0^{-1} \Delta_1$ and $\Delta_0^{-1} \Delta_2$ commute. In the nonsingular case the 2EP (7.1) has $n_1 n_2$ eigenvalues and it can be solved with a variant of the QZ algorithm on (7.3); see [18].

It turns out that for many problems occurring in practice both pencils (Δ_1, Δ_0) and (Δ_2, Δ_0) are singular and we have a singular 2EP [31]. Applications include delay-differential equations [20], quadratic 2EPs [32, 19], model updating [5], and roots of systems of bivariate polynomials [37, 2].

The eigenvalues of a singular 2EP (7.1) are the finite regular eigenvalues of (7.3); see section 3.3. There exists a staircase type algorithm that works on both singular pencils (7.3) simultaneously and extracts finite regular eigenvalues; see [32] and an implementation in [35]. However, as illustrated in Examples 6.3 and 6.4, a staircase algorithm may fail. In this section we propose an alternative method that may be applied to a singular 2EP, which in some cases finds finite regular eigenvalues when the staircase algorithm fails, while in some other cases the situation is exactly the opposite.

We can apply Algorithm 1 to $\Delta_1 z = \lambda \Delta_0 z$, one of the two singular pencils in (7.3), to compute the λ_i components of eigenvalues (λ_i, μ_i) . This is, however, only half of the required information and for each λ_i we have to find the corresponding μ_i . Subsequently, we insert $\lambda = \lambda_i$ into (7.1) and search for common eigenvalues μ of a pair of pencils $(A_1 - \lambda_i B_1) - \mu C_1$ and $(A_2 - \lambda_i B_2) - \mu C_2$ that may be singular as well. We detect the common eigenvalues by comparing the sets of computed eigenvalues for the first and the second pencil, for which we use Algorithm 1 again. The overall method is given in Algorithm 2.

Algorithm 2. Computing finite regular eigenvalues of a singular 2EP.

Input: Matrices $A_1, B_1, C_1, A_2, B_2, C_2$ from (7.1) which provide Δ_1 and Δ_0 from (7.2); threshold δ (default $\delta = \varepsilon^{1/2}$), and parameters for Algorithm 1.

Output: Finite regular eigenvalues of (7.1).

- 1: Compute finite eigenvalues $\lambda_1, \dots, \lambda_r$ of $\Delta_1 - \lambda\Delta_0$ using Algorithm 1.
 - 2: **for** $j = 1, \dots, r$
 - 3: Compute eigenvalues $\mu_1^{(1)}, \dots, \mu_{m_1}^{(1)}$ of $(A_1 - \lambda_j B_1) - \mu C_1$ using Algorithm 1.
 - 4: Compute eigenvalues $\mu_1^{(2)}, \dots, \mu_{m_2}^{(2)}$ of $(A_2 - \lambda_j B_2) - \mu C_2$ using Algorithm 1.
 - 5: Reorder eigenpairs: $|\mu_1^{(1)} - \mu_1^{(2)}| \leq \dots \leq |\mu_m^{(1)} - \mu_m^{(2)}|$ for $m = \min(m_1, m_2)$.
 - 6: **for** $k = 1, \dots, m$
 - 7: **if** $|\mu_k^{(1)} - \mu_k^{(2)}| < \delta$ **then** add $(\lambda_j, \frac{1}{2}(\mu_k^{(1)} + \mu_k^{(2)}))$ to list of eigenvalues.
-

Some remarks about Algorithm 2 are in order.

- If we know that each eigenvalue has a unique λ component, then we can replace lines 6 and 7 by selecting $(\lambda_j, \frac{1}{2}(\mu_1^{(1)} + \mu_1^{(2)}))$ regardless of the difference $|\mu_1^{(1)} - \mu_1^{(2)}|$.
- If $n_1 = n_2 = n$, then the complexity of line 1 is $\mathcal{O}(n^6)$, while the complexity of lines 2 to 7 is at most $\mathcal{O}(n^5)$ in case $r = \mathcal{O}(n^2)$.

Example 7.1. Consider a system of bivariate polynomials (cf. [37, Ex. 5.3, 6.2, 6.4])

$$\begin{aligned}
 p_1(\lambda, \mu) &= 1 + 2\lambda + 3\mu + 4\lambda^2 + 5\lambda\mu + 6\mu^2 + 7\lambda^3 + 8\lambda^2\mu + 9\lambda\mu^2 + 10\mu^3 = 0, \\
 p_2(\lambda, \mu) &= 10 + 9\lambda + 8\mu + 7\lambda^2 + 6\lambda\mu + 5\mu^2 + 4\lambda^3 + 3\lambda^2\mu + 2\lambda\mu^2 + \mu^3 = 0.
 \end{aligned}$$

Using a uniform determinantal representation from [2], we write the above system as a 2EP of the form

$$\begin{aligned}
 A_1 + \lambda B_1 + \mu C_1 &= \begin{bmatrix} 0 & 0 & 4 + 7\lambda & 1 & 0 \\ 0 & 5 + 8\lambda & 2 & -\lambda & 1 \\ 6 + 9\lambda + 10\mu & 3 & 1 & 0 & -\lambda \\ 1 & -\mu & 0 & 0 & 0 \\ 0 & 1 & -\mu & 0 & 0 \end{bmatrix}, \\
 A_2 + \lambda B_2 + \mu C_2 &= \begin{bmatrix} 0 & 0 & 7 + 4\lambda & 1 & 0 \\ 0 & 6 + 3\lambda & 9 & -\lambda & 1 \\ 5 + 2\lambda + \mu & 8 & 10 & 0 & -\lambda \\ 1 & -\mu & 0 & 0 & 0 \\ 0 & 1 & -\mu & 0 & 0 \end{bmatrix},
 \end{aligned}$$

where $p_i(\lambda, \mu) = \det(A_i + \lambda B_i + \mu C_i)$ for $i = 1, 2$. The obtained 2EP is singular and has 9 regular eigenvalues (λ_j, μ_j) which are exactly the 9 solutions of the initial polynomial system.

If we apply Algorithm 2 to the above problem, we get all 9 solutions. In line 2 we compute first components $\lambda_1, \dots, \lambda_9$ as finite eigenvalues of the corresponding singular pencil $\Delta_1 - \lambda\Delta_0$ from (7.3), whose KCF contains 4 L_0 , 4 L_0^T , 2 N_4 , 1 N_2 , 2 N_1 , and 9 J_1 blocks. For each λ_j we compute the candidates for μ_j in lines 4 and 5, where the KCF of singular pencils $(A_i - \lambda_j B_i) - \mu C_i$ contains 1 N_2 and 3 J_1 blocks for $i = 1, 2$ and $j = 1, \dots, 9$.

We remark that the above approach might also fail, in particular if we apply it to systems of bivariate polynomials of high degree. Some of the eigenvalues of $\Delta_1 - \lambda\Delta_0$ might be so ill-conditioned that the algorithm cannot separate them from the infinite eigenvalues. In such a case a possible solution would be to apply computation in higher precision, using, e.g., the Multiprecision Computing Toolbox [36].

8. Conclusions. We have proposed a method to approximate the finite eigenvalues of a singular pencil by means of a *rank-completing perturbation*. The use of such a perturbation ensures that, generically, the finite and infinite eigenvalues remain fixed, while there appear newly generated eigenvalues. For many problems we can well distinguish the original eigenvalues from the newly created ones by considering the angles of the eigenvectors with respect to the perturbation spaces, and the condition numbers of the eigenvalues. Thus, this method may be useful for a wide range of applications.

The proposed method could be an alternative to the class of staircase algorithms, such as, e.g., Guptri [17], or a staircase type algorithm for singular two-parameter eigenvalue problems ([32] as implemented in [35]). These methods can be rapid and accurate; however, the key part of staircase techniques is a number of rank decisions, which can be difficult and ill-posed—see, e.g., [14] and Examples 6.3 and 6.4. In some cases, when these methods fail to return even a single eigenvalue, the newly proposed method may still compute all or at least some of the eigenvalues.

A code for the approach developed in this paper is available in [35].

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