PERTURBATION OF SIMPLE EIGENVALUES OF TIME-INVARIANT SINGULAR LINEAR SYSTEMS WITH ALGEBRAIC OUTPUT EQUATION

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Abstract

It is well known that the eigenvalues of a linear dynamical system play a key role in determining the response of the system. Small perturbations in these values may change drastically the dynamics of the system. In this work an analysis of the small perturbation of simple eigenvalues of a time-invariant singular linear system is presented.

Key words

Control systems, eigenvalues, perturbation.

1 Introduction

Let us consider a finite-dimensional singular linear time-invariant system

$$\left.\begin{aligned} E\dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned}\right\} \quad x(t_0) = x_0, \qquad (1)$$

where x is the state vector, u is the input (or control) vector, $E, A \in M_{n\times q}(\mathbb{C})$, $B \in M_{n\times m}(\mathbb{C})$, $C \in M_{p\times q}(\mathbb{C})$ and $\dot{x} = dx/dt$. We will represent the systems as 4-tuples of matrices (E, A, B, C). In this paper we will consider the case where $n = q$. For the square case and if $E = I_n$ the systems are standard and we will denote them, as 3-tuples (A, B, C).

Singular systems appear in engineering systems such as electrical, chemical processing circuit or power systems, aircraft guidance and Control, mechanical industrial plants, acoustic noise control, among others, and they have attracted interest in recent years.

It is well known that the eigenvalues and eigenvectors of the system matrix play a key role in determining the response of the system. Sometimes it is possible to change the value of some eigenvalues introducing proportional and derivative feedback controls in the system and proportional and derivative output injection. The values of the eigenvalues that can not be modified by any feedback (proportional or derivative) and/or output injection (proportional or derivative), correspond to the eigenvalues of the singular pencil $\begin{pmatrix} sE - A & B \\ C & 0 \end{pmatrix}$, that we will simply call eigenvalues of the system (E, A, B, C).

Perturbation theory of linear systems has been extensively studied over the last years starting from the works of Rayleigh and Schrodinger [Kato, 1980], and more recently different works as [Benner, Mehrmann and Xu, 2002] and [Rigatos, Siano and Pessolano, 2012], can be found. In [García-Planas and Tarragona, 2011],[García-Planas and Tarragona, 2012] M.I. García-Planas and S. Tarragona introduce the study to singular systems without algebraic output equation. The treatment of eigenvalues used is a tool for efficiently approximating the influence of small perturbations on different properties of the unperturbed system.

Small perturbations of simple eigenvalues with a change of parameters is a problem of general interest in applied mathematics and concretely, this study for the kind of systems under consideration have some interest because in the case where $m = p < n$, the most generic types of systems have $n - m$ simple eigenvalues.

This paper is an extended version of the paper presented by M.I. García-Planas and S. Tarragona to Physcon 2013 [García-Planas and Tarragona, 2013], and the key to the study is the given characterization of simple eigenvalues.

In the sequel and without lost of generality, we will consider systems such that matrices B and C have full rank and $m = p < n$.

2 Equivalent systems

An equivalence relation can be considered in the space of singular linear systems

Definition 2.1. *Two singular systems (E', A', B', C') and (E, A, B, C) will be called equivalent if, and only if, there exist matrices $P, Q \in Gl(n; \mathbb{C})$, $R \in Gl(m; \mathbb{C})$, $S \in Gl(p; \mathbb{C})$, $F^B_A, F^B_E \in M_{m\times n}(\mathbb{C})$ and $F^C_A, F^C_E \in M_{n\times p}(\mathbb{C})$ such that*

$$\begin{array}{l}(E', A', B', C') = \\ (QEP + F^C_E CP + QBF^B_E, QAP + F^C_A CP + QBF^B_A, \\ \qquad QBR, SCP).\end{array} \tag{2}$$

It is easy to check that this relation is an equivalence relation.

If system (E, A, B, C), is in such way that there exist matrices F^B_E and/or F^C_E such that $E + BF^B_E + F^C_E C$ is invertible, then it is called standardizable, and in this case there exist matrices P, Q, F^B_E, F^C_E such that $QEP + QBF^B_E + F^C_E CP = I_n$. Consequently this system is equivalent to a standard one. Notice that the property "to be standardizable" is invariant under the equivalence relation being considered.

If the original system is standard and if we want to preserve this condition under the equivalence relation we restrict the operation to the case where $Q = P^{-1}$, $F^B_E = 0$ and $F^C_E = 0$.

2.1 Eigenstructure

The eigenvalue concept defined for standard systems can be generalized to singular systems in the following manner

Definition 2.2. *Let (E, A, B, C) be a system. λ_0 is an eigenvalue of this system if and only if*

$$\operatorname{rank}\begin{pmatrix}\lambda_0 E - A & B \\ C & 0\end{pmatrix} < \operatorname{rank}\begin{pmatrix}\lambda E - A & B \\ C & 0\end{pmatrix}.$$

We denote by $\sigma(E, A, B, C)$ the set of eigenvalues of the system (E, A, B, C) and we call it the spectrum of the system.

Proposition 2.1. *Let (E, A, B, C) be a system. The spectrum of this system is invariant under equivalence relation considered.*

Proof. It suffices to observe that

$$\begin{array}{l}\operatorname{rank}\begin{pmatrix}\lambda E - A & B \\ C & 0\end{pmatrix} = \\ \operatorname{rank}\begin{pmatrix}Q & \lambda F^C_E - F^C_A \\ 0 & S\end{pmatrix}\begin{pmatrix}\lambda E - A & B \\ C & 0\end{pmatrix}\begin{pmatrix}P & \\ \lambda F^B_E - F^B_A & R\end{pmatrix}.\end{array}$$

Definition 2.3. *i) $v_0 \in M_{n\times 1}(\mathbb{C})$ is an eigenvector of this system corresponding to the eigenvalue λ_0 if and only if, there exist a vector $w_0 \in M_{m\times 1}(\mathbb{C})$ such that*

$$\begin{pmatrix}\lambda_0(E + BF^B_E) - (A + BF^B_A) & B \\ C & 0\end{pmatrix}\begin{pmatrix}v_0 \\ w_0\end{pmatrix} = 0,$$

for all F^B_E, F^B_A.

ii) $u_0 \in M_{1\times n}(\mathbb{C})$ is a left eigenvector of the system corresponding to the eigenvalue λ_0 if and only if, there exist a vector $\omega_0 \in M_{1\times p}(\mathbb{C})$ such that

$$\begin{pmatrix}u_0 & \omega_0\end{pmatrix}\begin{pmatrix}\lambda_0(E + F^C_E C) - (A + F^C_A C) & B \\ C & 0\end{pmatrix} = 0,$$

for all F^C_E, F^C_A.

Proposition 2.2. *Let λ_0 be an eigenvalue and v_0 an associated eigenvector of the (E, A, B, C). Then λ_0 is an eigenvalue and v_0 an associated eigenvector of $(E + BF^C_E + F^C_E C, A + BF^B_A + F^C_A C, B, C)$ for all F^B_E, F^C_E, F^B_A, F^C_A.*

Proof. Let $\overline{w}_0 = w_0 - (\lambda_0 F^B_E - F^B_A)v_0$.

$$\begin{array}{l}\begin{pmatrix}I & \lambda_0 F^C_E - F^C_A \\ 0 & I\end{pmatrix}\begin{pmatrix}\lambda_0 E - A & B \\ C & 0\end{pmatrix}\begin{pmatrix}I & 0 \\ \lambda_0 F^B_E - F^B_A & I\end{pmatrix}\begin{pmatrix}v_0 \\ \overline{w}_0\end{pmatrix} = \\ \begin{pmatrix}I & \lambda_0 F^C_E - F^C_A \\ 0 & I\end{pmatrix}\begin{pmatrix}\lambda_0 E - A & B \\ C & 0\end{pmatrix}\begin{pmatrix}v_0 \\ (\lambda_0 F^B_E - F^B_A)v_0 + \overline{w}_0\end{pmatrix} = \\ \begin{pmatrix}I & \lambda_0 F^C_E - F^C_A \\ 0 & I\end{pmatrix}\begin{pmatrix}\lambda_0 E - A & B \\ C & 0\end{pmatrix}\begin{pmatrix}v_0 \\ w_0\end{pmatrix} = \\ \begin{pmatrix}I & \lambda_0 F^C_E - F^C_A \\ 0 & I\end{pmatrix}\begin{pmatrix}0 \\ 0\end{pmatrix} = \begin{pmatrix}0 \\ 0\end{pmatrix}\end{array}$$

Proposition 2.3. *Let λ_0 be an eigenvalue and u_0 an associated left eigenvector of the (E, A, B, C). Then λ_0 is an eigenvalue and u_0 an associated left eigenvector of $(E + BF^C_E + F^C_E C, A + BF^B_A + F^C_A C, B, C)$ for all F^B_E, F^C_E, F^B_A, F^C_A.*

Proof. Analogous to the proof of proposition 2.2, taking $\overline{\omega}_0 = \omega_0 - u_0(\lambda_0 F^C_E - F^C_A)$.

Remark 2.1. *Unlike the case of triples of matrices (E, A, B) (see [García-Planas and Tarragona, 2012]) If λ_0 is an eigenvalue of the 4-tuple (E, A, B, C) it is not necessarily a generalized eigenvalue of the pair (E, A), as we can see in the following example.*

Example 2.1. *Let (E, A, B, C) be a system with $E = I$, $A = \begin{pmatrix}0 & 0 \\ 1 & 2\end{pmatrix}$, $B = \begin{pmatrix}3 \\ 0\end{pmatrix}$, $C = \begin{pmatrix}1 & 1\end{pmatrix}$.*

$$\det\begin{pmatrix}\lambda E - A & B \\ C & 0\end{pmatrix} = -3\lambda + 3 = 0.$$

Then, the eigenvalue of the system is $\lambda = 1$. Observe that $v_0 = (-3,3)^t$ is an eigenvector associated to $\lambda = 1$ (there exist $w_0 = 1$).

But $\det(\lambda E - A) = \lambda(\lambda - 2)$, so the eigenvalues of the pair (E, A) are $\lambda_1 = 0$ and $\lambda_2 = 2$.

We will distinguish one type of eigenvalue that in some sense is generic.

Definition 2.4. *An eigenvalue λ_0 of the system (E, A, B, C) is called simple if and only if verifies the following conditions*

i) $\operatorname{rank}\begin{pmatrix}\lambda_0 E - A & B\\ C & 0\end{pmatrix} = \operatorname{rank}\begin{pmatrix}\lambda E - A & B\\ C & 0\end{pmatrix} - 1,$

and

ii) $$\operatorname{rank}\begin{pmatrix}\lambda_0 E - A & B & 0 & 0\\ C & 0 & 0 & 0\\ E & 0 & \lambda_0 E - A & B\\ 0 & 0 & C & 0\end{pmatrix} = \operatorname{rank}\begin{pmatrix}\lambda_0 E - A & B\\ C & 0\end{pmatrix} + \operatorname{rank}\begin{pmatrix}\lambda E - A & B\\ C & 0\end{pmatrix}.$$

It is easy to proof the following proposition.

Proposition 2.4. *The simple character is invariant under equivalence relation considered.*

Proposition 2.5. *Let λ_0 be a simple eigenvalue of the standard system (A, B, C). Then, there exist an associate eigenvector v_0 and an associate left eigenvector u_0 such that $u_0 v_0 = 1$.*

Proof. If λ_0 is a simple eigenvalue, the system, this can be reduced to $\left(\begin{pmatrix}A_1 & 0\\ 0 & \lambda_0\end{pmatrix}, \begin{pmatrix}B_1\\ 0\end{pmatrix}, (C_1\ 0)\right)$, with $\operatorname{rank}\begin{pmatrix}\lambda_0 I - A_1 & B_1\\ C_1 & 0\end{pmatrix} = n - 1$.

In this reduced form it is easy to observe that $v_0 = (0, ..., 0, 1)^t$ is an eigenvector and $v_0 = (0, ..., 0, 1)$ is a left eigenvector verifying $u_0 v_0 = 1$. Now, taking into account propositions 2.2 and 2.3, we can check easily that $P v_0$ is an eigenvector of the system (A, B, C) and $u_0 P^{-1}$ is a left eigenvector for some invertible matrix P.

Remark 2.2. *In general, for singular systems this result fails.*

But, we have the following more general result.

Proposition 2.6. *Let λ_0 be a simple eigenvalue of the singular system (E, A, B, C) with $m = p = 1$ and $\operatorname{rank}\begin{pmatrix}\lambda E - A & B\\ C & 0\end{pmatrix} = n + 1$. Then, there exist an associate eigenvector v_0 and an associate left eigenvector u_0 such that $u_0 E v_0 \neq 0$.*

Proof. If λ_0 is a simple eigenvalue

$$\begin{pmatrix}\lambda_0 E - A & B & 0 & 0\\ C & 0 & 0 & 0\\ E & 0 & \lambda_0 E - A & B\\ 0 & 0 & C & 0\end{pmatrix}\begin{pmatrix}v_0\\ w_0\\ v_1\\ w_1\end{pmatrix} \neq 0$$

for all v_1 and w_1. So taking $v_1 = 0$ and $w_1 = 0$ we have that $E v_0 \neq 0$.

Suppose now that $u_0 E v_0 = 0$, in this case we have that

$0 \neq \begin{pmatrix}E v_0\\ 0\end{pmatrix} \in \operatorname{Ker}\begin{pmatrix}u_0 & \omega_0\end{pmatrix} = \operatorname{Im}\begin{pmatrix}\lambda_0 E - A & B\\ C & 0\end{pmatrix}$.

Then, $\begin{pmatrix}E v_0\\ 0\end{pmatrix} = \begin{pmatrix}\lambda_0 A - A & B\\ C & 0\end{pmatrix}\begin{pmatrix}v_1\\ w_1\end{pmatrix}$ for some $(v_1, w_1) \neq (v_0, w_0)$ because $E v_0 \neq 0$.

So

$$\begin{pmatrix}\lambda_0 E - A & B & 0 & 0\\ C & 0 & 0 & 0\\ E & 0 & \lambda_0 E - A & B\\ 0 & 0 & C & 0\end{pmatrix}\begin{pmatrix}v_0\\ w_0\\ v_1\\ w_1\end{pmatrix} = 0$$

ans λ_0 can not be simple. Therefore $u_0 E v_0 \neq 0$.

Remark 2.3. *Notice that, if $E = I$ the result coincides with the case of standard systems.*

3 Perturbation Analysis of Simple Eigenvalues

3.1 Perturbation Analysis of Simple Eigenvalues of Standard Systems

First of all we will remember the study done for the standard case. So, we consider systems in the form $\dot{x} = Ax + Bu$, $y = Cx$ with $A \in M_n(\mathbb{C})$, $B \in M_{n\times m}(\mathbb{C})$ and $C \in M_{m\times n}(\mathbb{C})$ represented as a triple of matrices (A, B, C).

Let (A, B, C) be a linear system and assume that the matrices A, B, C smoothly depend on the vector $p = (p_1, \dots, p_r)$ of real parameters. The function $(A(p), B(p), C(p))$ is called a multi-parameter family of linear systems. Eigenvalues of linear system functions are continuous functions $\lambda(p)$ of the vector of parameters. In this section, we are going to study the behavior of a simple eigenvalue of the family of linear systems $(A(p), B(p), C(p))$.

Let us consider a point p_0 in the parameter space and assume that $\lambda(p_0) = \lambda_0$ is a simple eigenvalue of $(A(p_0), B(p_0), C(p_0)) = (A_0, B_0, C_0)$, and $v(p_0) = v_0$ is an eigenvector, i.e. there exists $w_0 \in M_{m\times 1}(\mathbb{C})$ such that

$$\left.\begin{aligned}A_0 v_0 - B_0 w_0 = \lambda_0 v_0\\ C_0 v_0 = 0\end{aligned}\right\}.$$

Equivalently

$$\left.\begin{array}{r}(A_0 + B_0F_A^B)v_0 - B_0w_0 = \lambda_0 v_0\\ C_0v_0 = 0\end{array}\right\},$$

$\forall F_A^B \in M_{m\times n}(\mathbb{C})$.

Now, we are going to review the behavior of a simple eigenvalue $\lambda(p)$ of the family of standard linear systems.

The eigenvector $v(p)$ corresponding to the simple eigenvalue $\lambda(p)$ determines a one-dimensional null-subspace of the matrix operator $\begin{pmatrix} A & B\\ C & 0\end{pmatrix}$ smoothly dependent on p. Hence, the eigenvector $v(p)$ (and corresponding $w(p)$ can be chosen as a smooth function of the parameters. We will try to obtain an approximation by means of their derivatives.

We rephrase the eigenvalue problem as follows

$$\left.\begin{array}{r}A(p)v(p) - B(p)w(p) = \lambda(p)v(p)\\ C(p)v(p) = 0.\end{array}\right\}. \tag{3}$$

Taking the derivatives with respect to p_i at the point p_0, we obtain

$$\left.\begin{array}{r}\left(\frac{\partial\lambda(p)}{\partial p_i}I - \frac{\partial A(p)}{\partial p_i}\right)_{|p_0} v_0 + \frac{\partial B(p)}{\partial p_i}_{|p_0} w_0 =\\ (A_0-\lambda_0 I)\frac{\partial v(p)}{\partial p_i}_{|p_0} - B_0\frac{\partial w(p)}{\partial p_i}_{|p_0}\\ \frac{\partial C(p)}{\partial p_i}_{|p_0} v_0 = -C_0\frac{\partial v(p)}{\partial p_i}_{|p_0}\end{array}\right\}. \tag{4}$$

This is a linear equation system for the unknowns $\frac{\partial\lambda(p)}{\partial p_i}$, $\frac{\partial v(p)}{\partial p_i}$ and $\frac{\partial w(p)}{\partial p_i}$.

Lemma 3.1. *Let v_0 and u_0 be an eigenvector and a left eigenvector respectively, corresponding to the simple eigenvalue λ_0 of the system (E, A, B, C). Then, the matrix*

$$T = \begin{pmatrix}\lambda_0 I - A_0 & B_0\\ C_0 & 0\end{pmatrix} + \begin{pmatrix} v_0u_0 & 0\\ 0 & 0\end{pmatrix}$$

has full rank.

Proof. It suffices to consider the system in the reduced form $\left(\begin{pmatrix}A_1 & 0\\ 0 & \lambda_0\end{pmatrix}, \begin{pmatrix}B_1\\ 0\end{pmatrix}, \begin{pmatrix}C_1 & 0\end{pmatrix}\right)$.

Theorem 3.1. *The system (4) has a solution if and only if*

$$\begin{pmatrix}u_0 & \omega_0\end{pmatrix}\begin{pmatrix}\frac{\partial\lambda(p)}{\partial p_i}I - \frac{\partial A(p)}{\partial p_i} & \frac{\partial B(p)}{\partial p_i}\\ \frac{\partial C(p)}{\partial p_i} & 0\end{pmatrix}\begin{pmatrix}v_0\\ w_0\end{pmatrix} = 0 \tag{5}$$

where u_0 is a left eigenvector for the simple eigenvalue λ_0 of the system (A_0, B_0, C_0).

Proof. The system (4) can be rewritten as

$$\begin{array}{l}\begin{pmatrix}\frac{\partial\lambda(p)}{\partial p_i}I - \frac{\partial A(p)}{\partial p_i} & \frac{\partial B(p)}{\partial p_i}\\ \frac{\partial C(p)}{\partial p_i} & 0\end{pmatrix}_{|p_0}\begin{pmatrix}v_0\\ w_0\end{pmatrix} =\\ \begin{pmatrix}A_0-\lambda_0 I & -B_0\\ -C_0 & 0\end{pmatrix}\begin{pmatrix}\frac{\partial v(p)}{\partial p_i}\\ \frac{\partial w(p)}{\partial p_i}\end{pmatrix}_{|p_0}\end{array} \tag{6}$$

We have that (4) has a solution if and only if (6) has.

Premultiplying both sides of the equation (6), by (u_0, ω_0)

$$\begin{array}{l}\begin{pmatrix}u_0 & \omega_0\end{pmatrix}\begin{pmatrix}\frac{\partial\lambda(p)}{\partial p_i}I - \frac{\partial A(p)}{\partial p_i} & \frac{\partial B(p)}{\partial p_i}\\ \frac{\partial C(p)}{\partial p_i} & 0\end{pmatrix}_{|p_0}\begin{pmatrix}v_0\\ w_0\end{pmatrix} =\\ \begin{pmatrix}u_0 & \omega_0\end{pmatrix}\begin{pmatrix}\frac{\partial\lambda(p)}{\partial p_i}I & 0\\ 0 & 0\end{pmatrix}_{|p_0}\begin{pmatrix}v_0\\ w_0\end{pmatrix} -\\ \quad\begin{pmatrix}u_0 & \omega_0\end{pmatrix}\begin{pmatrix}\frac{\partial A(p)}{\partial p_i} & -\frac{\partial B(p)}{\partial p_i}\\ -\frac{\partial C(p)}{\partial p_i} & 0\end{pmatrix}_{|p_0}\begin{pmatrix}v_0\\ w_0\end{pmatrix} = 0.\end{array}$$

We obtain a solution for $\frac{\partial\lambda(p)}{\partial p_i}_{|(\lambda_0;p_0)}$.

$$\frac{\partial\lambda(p)}{\partial p_i}_{|p_0} = \frac{\begin{pmatrix}u_0 & \omega_0\end{pmatrix}\begin{pmatrix}\frac{\partial A(p)}{\partial p_i} & -\frac{\partial B(p)}{\partial p_i}\\ -\frac{\partial C(p)}{\partial p_i} & 0\end{pmatrix}_{|p_0}\begin{pmatrix}v_0\\ w_0\end{pmatrix}}{u_0v_0}.$$

Using the normalization condition, that is to say, taking v_0 such that $u_0v_0 = 1$, we have:

$$\frac{\partial\lambda(p)}{\partial p_i}_{|p_0} = \begin{pmatrix}u_0 & \omega_0\end{pmatrix}\begin{pmatrix}\frac{\partial A(p)}{\partial p_i} & -\frac{\partial B(p)}{\partial p_i}\\ -\frac{\partial C(p)}{\partial p_i} & 0\end{pmatrix}_{|p_0}\begin{pmatrix}v_0\\ w_0\end{pmatrix}.$$

Knowing $\frac{\partial\lambda(p)}{\partial p_i}_{|p_0}$ we can deduce $\frac{\partial v(p)}{\partial p_i}_{|p_0}$.

First of all, we observe that if $u_0v_0 = 1$, then $u_0v(p) \neq 0$ and we can take $v(p)$ such that $u_0v(p) = 1$ (normalization condition, it suffices to take as $v(p)$ the vector $\frac{1}{u_0v(p)}v(p)$). So

$$\frac{\partial u_0v(p)}{\partial p_i} = u_0\frac{\partial v(p)}{\partial p_i} = 0.$$

Consequently we can consider the compatible equivalent system:

$$\begin{array}{l}\begin{pmatrix}\frac{\partial\lambda(p)}{\partial p_i} - \frac{\partial A(p)}{\partial p_i} & \frac{\partial B(p)}{\partial p_i}\\ \frac{\partial C(p)}{\partial p_i} & 0\end{pmatrix}_{|p_0}\begin{pmatrix}v_0\\ w_0\end{pmatrix} =\\ \begin{pmatrix}A_0-\lambda_0 I + v_0u_0 & -B_0\\ -C_0 & 0\end{pmatrix}\begin{pmatrix}\frac{\partial v(p)}{\partial p_i}\\ \frac{\partial w(p)}{\partial p_i}\end{pmatrix}_{|p_0}\end{array} \tag{7}$$

In our particular case where $m = p$, the system has a unique solution

$$\begin{pmatrix} \frac{\partial v(p)}{\partial p_i} \\ \frac{\partial w(p)}{\partial p_i} \end{pmatrix}_{|p_0} = T^{-1} \begin{pmatrix} \frac{\partial \lambda(p)}{\partial p_i} - \frac{\partial A(p)}{\partial p_i} & \frac{\partial B(p)}{\partial p_i} \\ \frac{\partial C(p)}{\partial p_i} & 0 \end{pmatrix}_{|p_0} \begin{pmatrix} v_0 \\ w_0 \end{pmatrix}.$$

Taking the partial derivative $\partial^2/\partial p_i \partial p_j$ on both sides of both equations in the eigenvalue problem (3), we can obtain a second order approximation for eigenvalues.

3.2 Perturbation Analysis of Simple Eigenvalues of Singular Systems

Now we consider singular systems as in (1). In this case the eigenvalue problem is written as

$$\left.\begin{aligned} A(p)v(p) - B(p)w(p) = \lambda(p)E(p)v(p) \\ C(p)v(p) = 0. \end{aligned}\right\}. \tag{8}$$

Taking the derivatives with respect to p_i, we have

$$\left.\begin{aligned} \left(\frac{\partial \lambda(p)}{\partial p_i}E(p) + \lambda(p)\frac{\partial E(p)}{\partial p_i} - \frac{\partial A(p)}{\partial p_i}\right)v(p) + \frac{\partial B(p)}{\partial p_i}w(p) \\ = (A(p) - \lambda(p)E(p))\frac{\partial v(p)}{\partial p_i} - B(p)\frac{\partial w(p)}{\partial p_i} \\ \frac{\partial C(p)}{\partial p_i}v(p) = -C(p)\frac{\partial v(p)}{\partial p_i} \end{aligned}\right\}.$$

At the point p_0, we obtain

$$\left.\begin{aligned} \left(\frac{\partial \lambda(p)}{\partial p_i}E_0 + \lambda_0\frac{\partial E(p)}{\partial p_i} - \frac{\partial A(p)}{\partial p_i}\right)_{|p_0} v_0 + \frac{\partial B(p)}{\partial p_i}_{|p_0} w_0 \\ = (A_0 - \lambda_0 E)\frac{\partial v(p)}{\partial p_i}_{|p_0} - B_0\frac{\partial w(p)}{\partial p_i}_{|p_0} \\ \frac{\partial C(p)}{\partial p_i}_{|p_0} v_0 = -C_0\frac{\partial v(p)}{\partial p_i}_{|p_0} \end{aligned}\right\}. \tag{9}$$

This is a linear equation system for the unknowns $\frac{\partial \lambda(p)}{\partial p_i}$, $\frac{\partial v(p)}{\partial p_i}$ and $\frac{\partial w(p)}{\partial p_i}$.

Suppose now, systems (E, A, B, C) with $m = p = 1$ and rank $\begin{pmatrix} \lambda E - A & B \\ C & 0 \end{pmatrix} = n + 1$.

Lemma 3.2. *Let v_0 and u_0 be an eigenvector and a left eigenvector respectively, corresponding to the simple eigenvalue λ_0 of the system (E, A, B, C). Then, the matrix*

$$T = \begin{pmatrix} \lambda_0 E - A_0 & B_0 \\ C_0 & 0 \end{pmatrix} + \begin{pmatrix} E_0 v_0 u_0 E_0 & 0 \\ 0 & 0 \end{pmatrix}$$

has full rank.

Proof. First of all we proof that $E_0 v_0 u_0 E_0 \neq 0$.

$$\begin{pmatrix} u_0 & \omega_0 \end{pmatrix} \begin{pmatrix} \lambda_0 E_0 - A_0 + E_0 v_0 u_0 E_0 & B_0 \\ C_0 & 0 \end{pmatrix} \begin{pmatrix} v_0 \\ w_0 \end{pmatrix} = \begin{pmatrix} u_0 & \omega_0 \end{pmatrix} \begin{pmatrix} E_0 v_0 u_0 E_0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v_0 \\ w_0 \end{pmatrix} = (u_0 E_0 v_0)^2 \neq 0,$$

so, $E_0 v_0 u_0 E_0 \neq 0$.

In the other hand $v_0 \notin \operatorname{Ker} E_0 v_0 u_0 E_0$, because $0 \neq (u_0 E_0 v_0)^2 = u_0(E_0 v_0 u_0 E_0 v_0)$.

Suppose now, that

$$\begin{pmatrix} \lambda_0 E_0 - A_0 + E_0 v_0 u_0 E_0 & B_0 \\ C_0 & 0 \end{pmatrix} \begin{pmatrix} v \\ w \end{pmatrix} = 0$$

for some vectors v and w.

Then

$$0 = \begin{pmatrix} u_0 & \omega_0 \end{pmatrix} \begin{pmatrix} \lambda_0 E_0 - A_0 + E_0 v_0 u_0 E_0 & B_0 \\ C_0 & 0 \end{pmatrix} \begin{pmatrix} v \\ w \end{pmatrix} = \begin{pmatrix} u_0 & \omega_0 \end{pmatrix} \begin{pmatrix} E_0 v_0 u_0 E_0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v \\ w \end{pmatrix} = u_0 E_0 v_0 u_0 E_0 v.$$

Taking into account that $u_0 E_0 v_0 \neq 0$ we have that $u_0 E_0 v = 0$, so $E_0 v_0 u_0 E_0 v = 0$, then v is an eigenvector of the system corresponding to the eigenvalue λ_0 linearly independent of v_0, but λ_0 is simple.

Theorem 3.2. *The system (9) has a solution if and only if*

$$\begin{pmatrix} u_0 & \omega_0 \end{pmatrix} \begin{pmatrix} \frac{\partial \lambda(p)}{\partial p_i}E_0 + \lambda_0\frac{\partial E}{\partial p_i} - \frac{\partial A(p)}{\partial p_i} & \frac{\partial B(p)}{\partial p_i} \\ \frac{\partial C(p)}{\partial p_i} & 0 \end{pmatrix}_{|p_0} \begin{pmatrix} v_0 \\ w_0 \end{pmatrix} = 0 \tag{10}$$

where u_0 is a left eigenvector for the simple eigenvalue λ_0 of the system (E_0, A_0, B_0, C_0).

Proof. Analogously to the proof of proposition 3.1 we observe that proposition 2.6 permits to clear the unknown $\frac{\partial \lambda(p)}{\partial p_i}$ from equation (10).

On the other hand, taking into account that $u_0 E_0 v_0 \neq 0$, we have that $u_0 E(p) v(p) \neq 0$ in a neighborhood of the origin. So, $u_0 E_0 \frac{\partial v(p)}{\partial p} = 0$. Lemma 3.2 permits to obtain $\frac{\partial v(p)}{\partial p_i}$ and $\frac{\partial w(p)}{\partial p_i}$.

4 Conclusions

In this work a characterization of simple eigenvalue of a time-invariant singular linear system is given and an analysis of small perturbation of simple eigenvalues is presented.

For the analysis it was considered that a disturbance of the system can be interpreted as a family of systems depending differentiably of a collection of parameters.

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