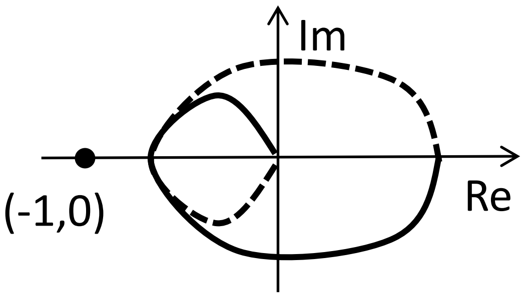
Advanced new results in classical control and electrical network theory

M. Bucolo, A. Buscarino, L. Fortuna, M. Frasca

IASI, CNR, Roma, September 18th 2020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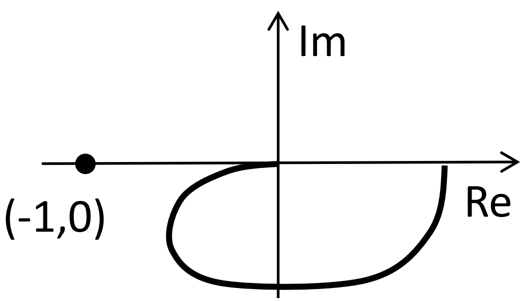
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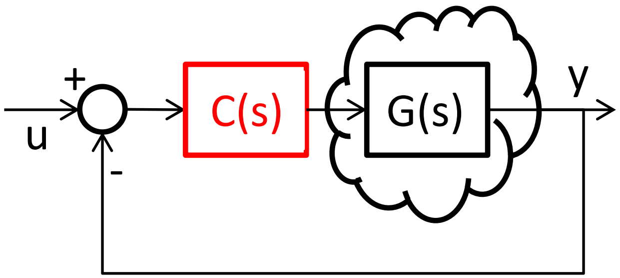
Lecture Notes in Control and Information Sciences
168
P. Dorato, L. Fortuna, G. Muscato
Robust Control for Unstructured Perturbations – An Introduction
Springer-Verlag
Berlin Heidelberg GmbH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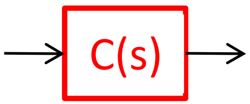
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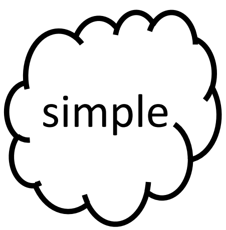
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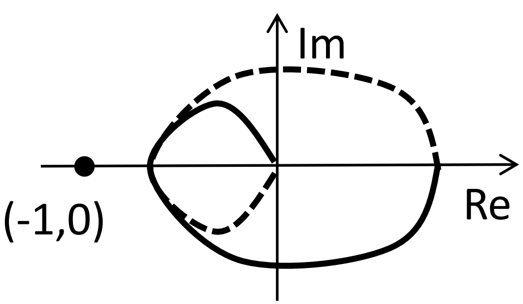
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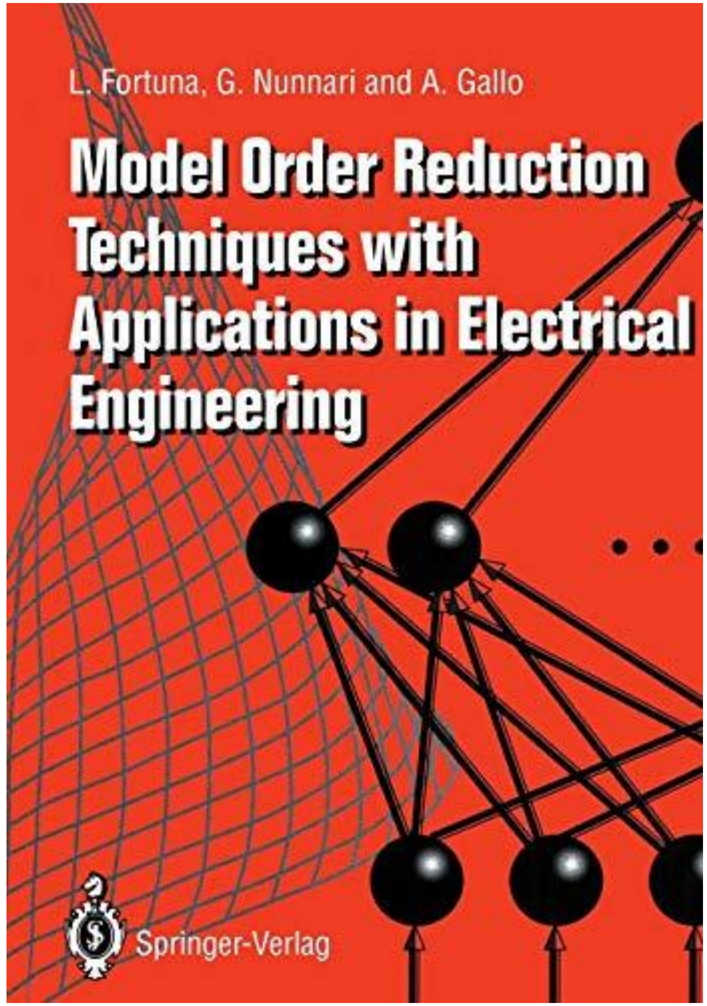
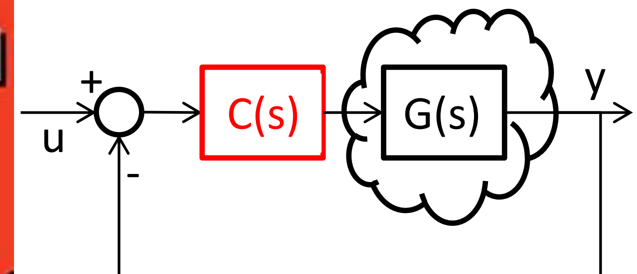

L. Fortuna, G. Nunnari and A. Gallo
Model Order Reduction Techniques with Applications in Electrical Engineering
Springer-Verlag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LINEAR CONTINUOUS-TIME TIME-INVARIANT SYSTEMS

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathrm{A}\mathbf{x}(t) + \mathrm{B}\mathbf{u}(t) \\ \mathbf{y}(t) &= \mathrm{C}\mathbf{x}(t) + \mathrm{D}\mathbf{u}(t) \end{aligned} \tag{1}$$

with $\mathrm{A} \in \mathbb{R}^{n \times n}$, $\mathrm{B} \in \mathbb{R}^{n \times m}$, $\mathrm{C} \in \mathbb{R}^{m \times n}$ and $\mathrm{D} \in \mathbb{R}^{m \times m}$. $\mathbf{x} \in \mathbb{R}^n$ denotes the state vector, and $\mathbf{u}, \mathbf{y} \in \mathbb{R}^m$ the input and output vectors, respectively.

$$G(s) = \left[\begin{array}{c|c} \mathrm{A} & \mathrm{B} \\ \hline \mathrm{C} & \mathrm{D} \end{array}\right] = \mathrm{C}(s\mathrm{I} - \mathrm{A})^{-1}\mathrm{B} + \mathrm{D}$$

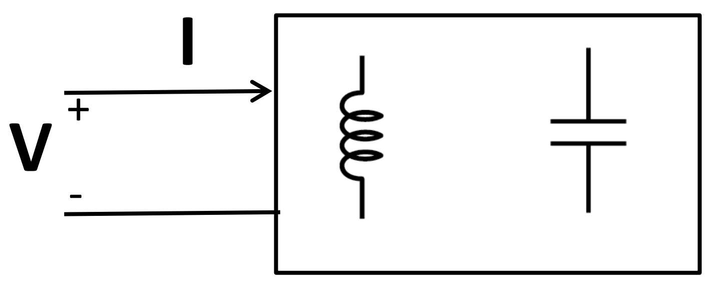
being s the Laplace variable.

FREQUENCY TRANSFORMATIONS

$$G(s) \qquad\qquad\qquad\qquad G(F(s))$$

$$s \leftarrow F(s)$$

In this discussion often we will consider F(s) as a loss-less function, defined as the impedance or the admittance of a bipole with only capacitors and inductors.



LINEAR DISCRETE-TIME TIME-INVARIANT SYSTEMS

$$\begin{cases} x(t+1) = \mathrm{A}x(t) + \mathrm{B}u(t) \\ y(t) = \mathrm{C}x(t) + \mathrm{D}u(t) \end{cases} \tag{1}$$

where $\mathrm{A} \in \mathbb{R}^{n,n}$, $\mathrm{B} \in \mathbb{R}^{n,m}$, $\mathrm{C} \in \mathbb{R}^{p,n}$, $\mathrm{D} \in \mathbb{R}^{m,p}$.

$$G(z) = \left[\begin{array}{c|c} \mathrm{A} & \mathrm{B} \\ \hline \mathrm{C} & \mathrm{D} \end{array}\right] = \mathrm{C}(z\cdot\mathrm{I} - \mathrm{A})^{-1}\mathrm{B} + \mathrm{D}$$

being z the zeta-transform variable.

Prof. Ing. Antonio **LEPSCHY**
dell'Università di Trieste

Prof. Ing. Antonio **RUBERTI**
dell'Università di Roma

LEZIONI DI
CONTROLLI AUTOMATICI

TEORIA DEI SISTEMI LINEARI E STAZIONARI

SECONDA EDIZIONE

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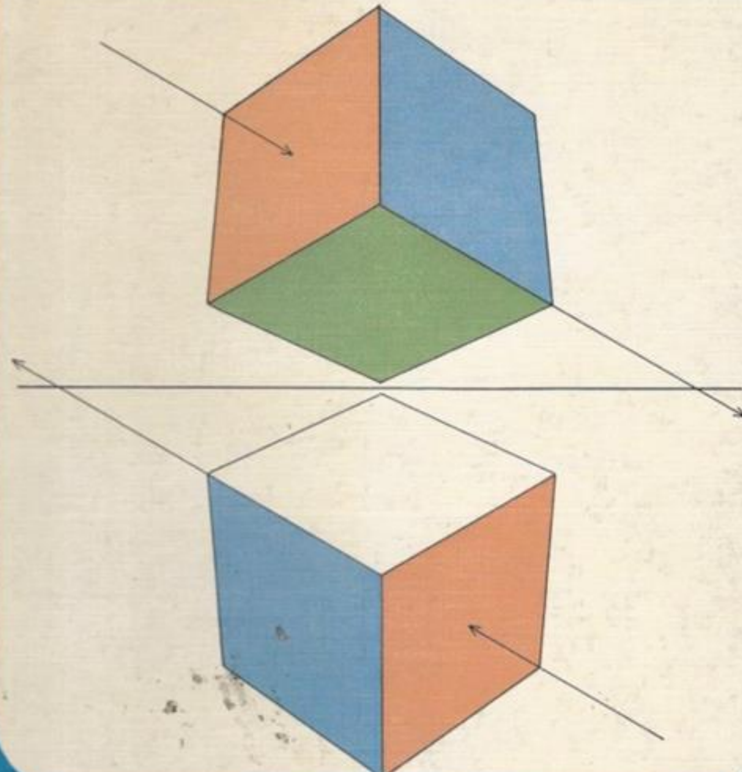
TEORIA DEI SISTEMI

Definizioni, proprietà, problemi - Stabilità dell'equilibrio - Stabilità dei sistemi lineari e linearizzazione - Stabilità in grande - Raggiungibilità e legge di controllo - Osservabilità e stima dello stato - Decomposizione canonica Funzioni di trasferimento - La realizzazione



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TEORIA DEI SISTEMI

PROGRAMMA
DI
MATEMATICA
FISICA
ELETTRONICA

BOLLATI BORINGHIERI

Invariants: $\sigma_1, \sigma_2, \ldots, \sigma_n$ singular values

$\mu_1, \mu_2, \ldots, \mu_n$ characteristic values

$\pi_1, \pi_2, \ldots, \pi_n$ positive real characteristic values

$\eta_1, \eta_2, \ldots, \eta_n$ bounded real characteristic values

IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. AC-26, NO. 1, FEBRUARY 1981

Principal Component Analysis in Linear Systems: Controllability, Observability, and Model Reduction

BRUCE C. MOORE

Abstract—Kalman's minimal realization theory involves geometric objects (controllable, unobservable subspaces) which are subject to structural instability. Specifically, arbitrarily small perturbations in a model may cause a change in the dimensions of the associated subspaces. This situation is manifested in computational difficulties which arise in attempts to apply textbook algorithms for computing a minimal realization.

Structural instability associated with geometric theories is not unique to control; it arises in the theory of linear equations as well. In this setting, the computational problems have been studied for decades and excellent tools have been developed for coping with the situation. One of the main goals of this paper is to call attention to *principal component analysis* (Hotelling, 1933), and an algorithm (Golub and Reinsch, 1970) for computing the *singular value decomposition* of a matrix. Together they form a powerful tool for coping with structural instability in dynamic systems.

As developed in this paper, principal component analysis is a technique for analyzing signals. (Singular value decomposition provides the computational machinery.) For this reason, Kalman's minimal realization theory is recast in terms of responses to injected signals. Application of the signal ana[illegible]controllability and [illegible]ility leads to a coordinate system in wh[illegible] the [illegible]internally balance[illegible]" mo[illegible]l has special properties. For asymptoti[illegible]lly [illegible]able system[illegible] this y[illegible]ds [illegible]orking [illegible]pp[illegible]ximati[illegible] [illegible] the controllable and [illegible]observable subspaces. [illegible] is proposed that a natural first step in model reduction is to apply the mechanics of minimal realization using these working subspaces.

I. INTRODUCTION

A COMMON and quite legitimate complaint directed toward multivariable control literature is that the apparent strength of the theory is not accompanied by strong numerical tools. Kalman's minimal realization theory [2], [3], for example, offers a beautifully clear picture of the structure of linear systems. Practically every linear systems text gives a d[illegible]ssion of controllability, observability, and minimal [illegible]tion. [illegible] associated textbook algorithms are far from satisfactory, however, serving mainly to illustrate the theory with textbook examples.

The problem with textbook algorithms for minimal realization theory is that they are based on the literal content of the theory and cannot cope with structural discontinuities (commonly called "structural instabilities") which arise. Uncontrollability corresponds to the situation where a certain subspace (controllable subspace) is proper, but arbitrarily small perturbations in an uncontrollable model may make the subspace technically not proper. Hence, for the perturbed model, the theory, taken literally, says that (assuming observability) there is no lower order model with the same impulse response matrix. There may well exist, however, a lower order model which has effectively the same impulse response matrix. There is a gap between minimal realization theory and the problem of finding a lower order approximation, which we shall refer to as the "model reduction problem."

The purpose of this paper is to show that there are some very useful tools which can be used to cope with these structural instabilities. Specifically, the tools will be applied to the model reduction problem. We shall draw heavily from the work of others in statistics and computer [illegible] where the problem of [illegible] ted with geometric theo[illegible] Principal component analysis, introd[illegible] in statistics (1933) by Hotelling [4], [5] will be used together with the algorithm by Golub and Reinsch [6] (see [7] for working code) for computing the singular value decomposition of [illegible]atrix. Dempster [8] gives an excellent geometric treat[illegible]ent of principal com[illegible] [illegible] [illegible] its history. A th[illegible] [illegible] value decomposition and its history is given in a recent paper by Klema and Laub [9]. There are excellent books [10]–[15] within the area of numerical linear algebra which explain how structural instabilities arise and are dealt with in the theory of linear equations.

[illegible]he material given i[illegible] [illegible] more general than tha[illegible] appearing [illegible] tions. [illegible] Section II minimal realization theory is reviewed from a "signal injection" viewpoint. The main advantage of this viewpoint is that the relevant subspaces are characterized in terms of responses to injected signals rather than in terms of the model parame[illegible] [illegible] full power of the ability to inject signals of various types is not fully exploited in this paper. Section III contains very general results which are valid whenever one is trying to find approximate linear relationships that exist among a [illegible] of time variables. In no other way is linearity required. (See [16] for ideas about nonlinear applications.) [illegible] Section IV controllability and observability analysis is discussed. Most of the effort is spent coming to grips with the problem of internal coordinate transformations.

Manuscript received July 17, [illegible]78; revised October 25, 1979 and June 5, 1980. This work was supported by the Natural Sciences and Engineering Research Council of Canada under Operating Grant [illegible]. This work represents a major revision of [illegible].

The author is with the Department of Electrical Engineering, University of Toronto, Toronto, Ont., Canada.

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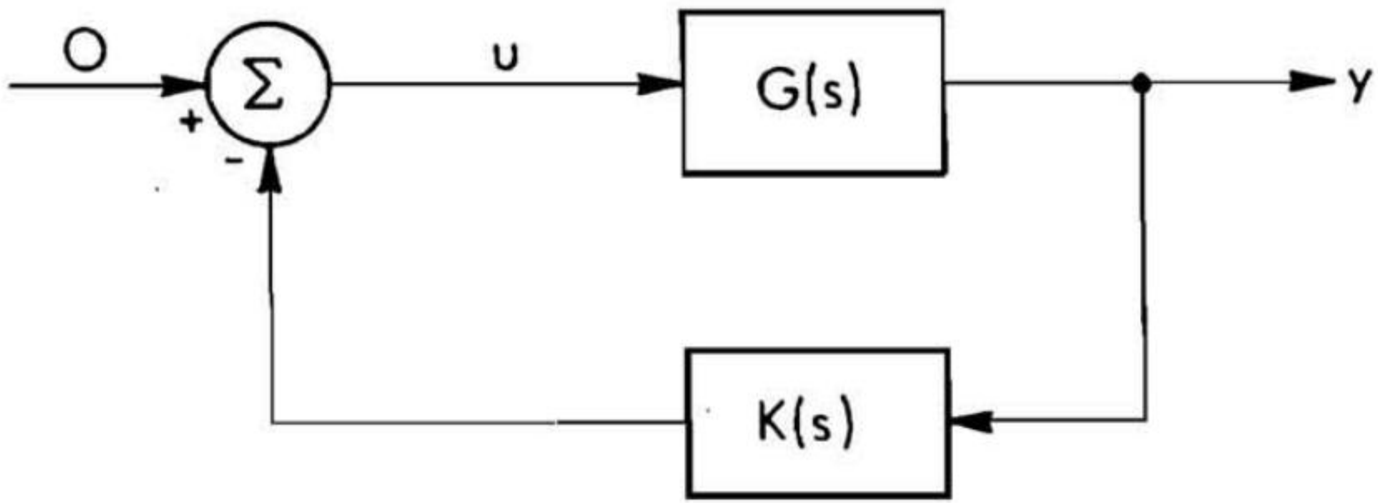
Die Grundlehren
der mathematischen Wissenschaften
in Einzeldarstellungen

V. M. Popov

Hyperstability of Control Systems

4.1. *Results from hyperstability theory*

Consider a system described by its transfer function $G(s)$ and let $K(s)$ be the transfer function of a particular compensator for $G(s)$, as in the Figure. Then one can conclude stability of the closed-loop system using the following two theorems from hyperstability theory.



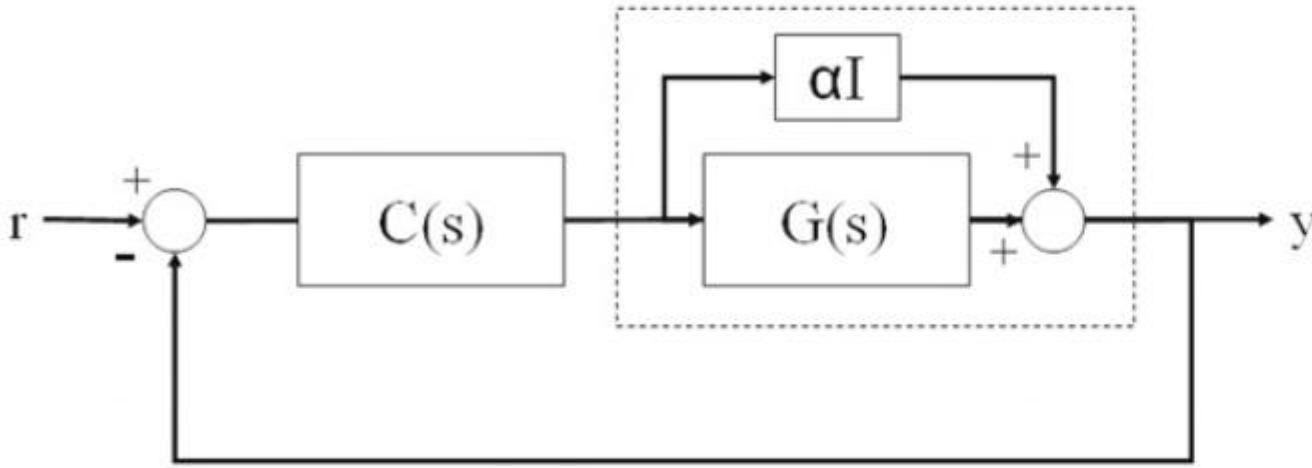
Hyperstable feedback system.

Theorem 4.1

The system shown in the Figure is stable if both $G(s)$ and $K(s)$ are positive real.

Theorem 4.2

The system shown in the Figure is asymptotically stable if either one of the two blocks, $G(s)$ and $K(s)$, is strictly positive real and the other positive real.



Feed-Forward Control Scheme

International Journal of Control
Vol. 85, No. 9, September 2012, 1235–1247

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An analytical approach to one-parameter MIMO systems passivity enforcement

A. Buscarino[ab], L. Fortuna[ab], M. Frasca[ab*] and M.G. Xibilia[c]

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(*Received 22 June 2011; final version received 30 March 2012*)

Stable linear time-invariant systems can be made passive by a feedforward action. In this article, an analytical approach to obtain the matrix which allows to enforce passivity in the system is proposed. This matrix depends only on one parameter, namely α. The introduced method is based on the calculation of the characteristic polynomial of the Hamiltonian matrix associated to the Positive Real problem. This polynomial is then used to derive a finite set of values of the paramet
dissipation can be selected. Numerical ex:

Keywords: passive systems; Positive Real

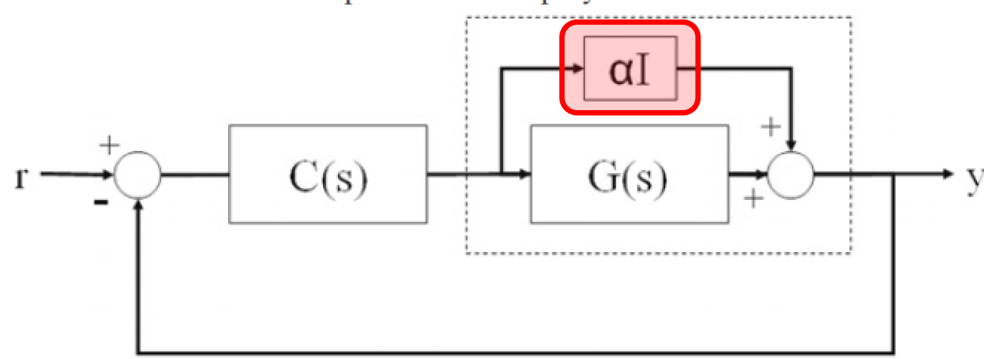

Figure 1. Control scheme consisting of a feedforward action making passive the system in the dashed box and a classical feedback loop.

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Invariance of characteristic values and L_∞ norm under lossless positive real transformations

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[a]DIEEI, Università degli Studi di Catania, Italy
[b]Dipartimento di Ingegneria, Università degli Studi di Messina, Italy

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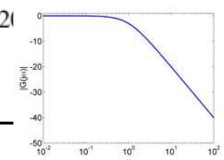
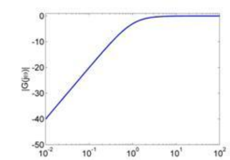
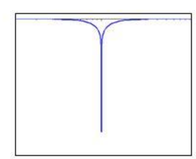
Available online 1 April 2016

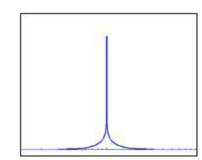


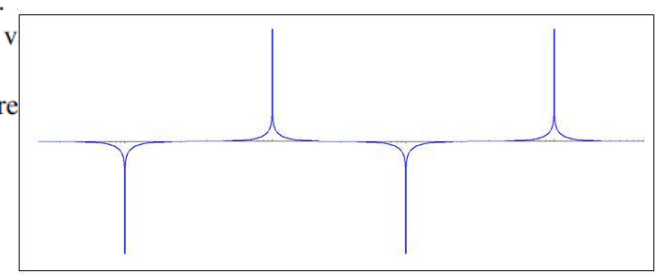


Abstract

In this paper the invariance of the characteristic values and of the L_∞ systems under lossless positive real transformations is proven. Given a matrix G(s), the transformation $s \leftarrow F(s)$ with $F(s)$ being an arbitrary los n_F is considered, and the algebraic Riccati equations (AREs) allowin transformed system G($F(s)$) are investigated. It is proven that, under su the AREs associated to system G($F(s)$) are related to those of G(s). G($F(s)$) and $G(s)$ have the same L_∞ norm and that the characteristic v each with multiplicity n_F.







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Systems & Control Letters

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Forward action to make a system negative imaginary

A. Buscarino, L. Fortuna, M. Frasca *

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Negative imaginary systems
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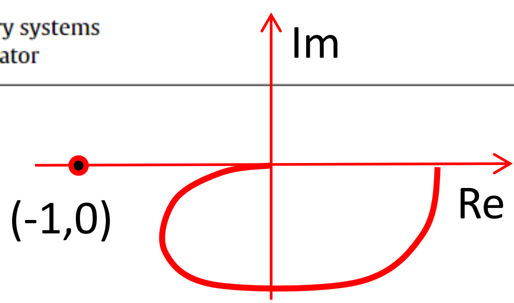
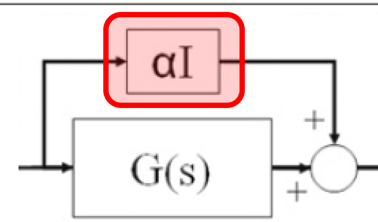
A B S T R A C T

In this letter a strategy to make a system negative imaginary is introduced. We prove that a dynamical forward action is effective to do it for Lyapunov stable systems and discuss how to design the forward compensator for SISO and MIMO systems. Some numerical examples are also included.





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Positive-real systems under lossless transformations: Invariants and reduced order models

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Abstract

In this paper, positive-real systems under lossless positive-real transformations are investigated. Let G(s) be the transfer function matrix of a continuous-time positive-real system of order n and $F(s)$ a lossless transfer function of order n_F. We prove here that the lossless positive-real transformed system, i.e. G($F(s)$), is also positive-real. Furthermore, the stochastic balanced representation of positive-real systems under lossless positive-real transformations is considered. In particular, it is proved that the positive-real characteristic values π_j of G($F(s)$) are the same of G(s) each with multiplicity n_F, independently from the choice of $F(s)$. This property is exploited in the design of reduced order models based on stochastic balancing. Finally, the proposed technique is a passivity preserving model order reduction method, since it is proven that the reduced order model of G($F(s)$) is still positive-real. An error bound for truncation related to the invariants π_j is also derived.

$\pi_1, \pi_2, \ldots, \pi_n$ positive real characteristic values

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Continuous time LTI systems under lossless positive real transformations: open-loop balanced representation and truncated reduced-order models

A. Buscarino[a], L. Fortuna[a], M. Frasca[a] and M. G. Xibilia[b]

[a]DIEEI, Università degli Studi di Catania, Italy; [b]Dipartimento di Ingegneria, Università degli Studi di Messina, Italy

ABSTRACT

In this paper, new results on the open-loop balanced representation of continuous time linear time-invariant systems are reported. More particularly, the effect of lossless positive real transformations on open-loop balanced representations is investigated with specific attention to the problem of model order reduction. The properties of systems where a lossless positive real transformation has been applied are discussed showing that, if the original system is open-loop balanced, the resulting transformed system is still open-loop balanced. Furthermore, the singular values of the transformed system are related to those of the original one. These results allow to derive a model order reduction strategy for this class of systems that leads to a consistent decrease of the numerical complexity. The proposed approach reveals to be of particular interest for the design of reduced-order systems with specific amplitude responses, including analog multiband filters.

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KEYWORDS
Continuous time LTI systems; model order reduction; open-loop balanced realisation; lossless positive real transformation

$\sigma_1, \sigma_2, \ldots, \sigma_n$ <u>singular values</u>

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DOI: https://doi.org/10.1080/00207179.2017.1364424

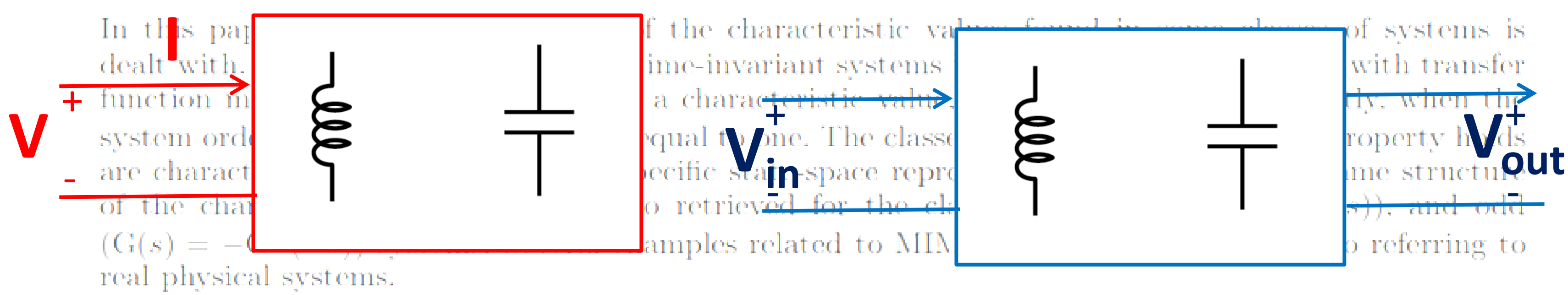
Check for updates

The structure of characteristic values for classes of linear time-invariant systems

Arturo Buscarino[a], Luigi Fortuna[a] and Mattia Frasca[a*]

[a]*DIEEI, Engineering Faculty, Università degli Studi di Catania, Catania, Italy.*

(*received xxxx*)



Keywords: Linear time-invariant systems; characteristic values.

$\mu_1, \mu_2, \ldots, \mu_n$ characteristic values

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Nyquist plots under frequency transformations

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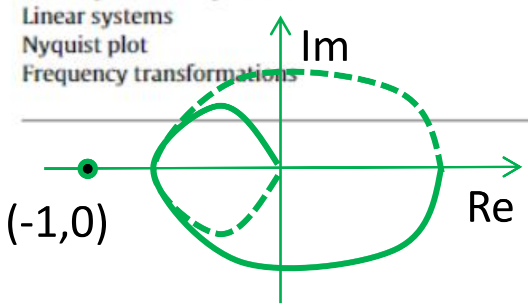
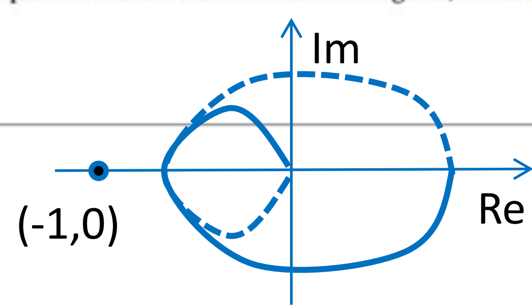
A B S T R A C T

The relevance of odd, and in particular loss-less, frequency transformations is well established in analog filter design. A loss-less frequency transformation $s \leftarrow F(s)$, in fact, allows to design multi-bandpass multi-bandstop filters as transformed systems $\bar{G}(s) = G(F(s))$ from an original prototype lowpass filter $G(s)$, by properly selecting $F(s)$. In this paper the invariance of the shape of the Nyquist plot for linear time-invariant continuous-time systems under a class of odd frequency transformations is proved. This result allows to determine closed-loop stability conditions for this class of transformed systems on the basis of the Nyquist's criterion referred to the original, lower order, system.





Systems & Control Letters 131 (2019) 104495

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Forward action to make time-delay systems positive-real or negative-imaginary

Maide Bucolo [a], Arturo Buscarino [a,b,*], Luigi Fortuna [a,b], Mattia Frasca [a,b]

[a] Dipartimento di Ingegneria Elettrica Elettronica e Informatica, University of Catania, Italy
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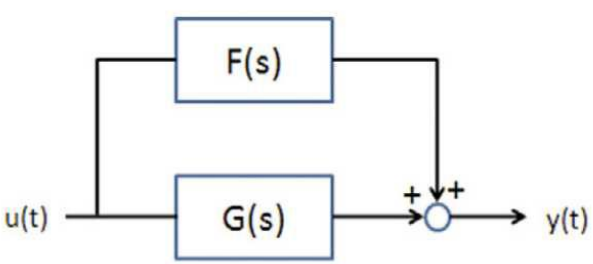

ABSTRACT

Positive-real and negative-imaginary systems are characterized by properties which make them particularly important in modeling physical devices, such as large-scale flexible structures or electric networks. This ı ... ve-
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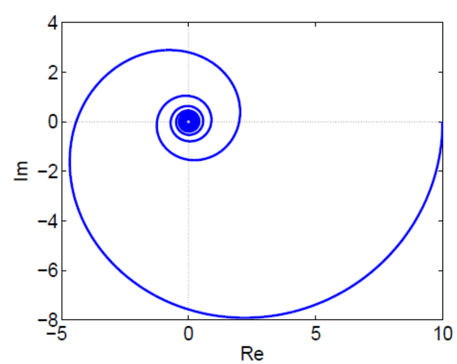
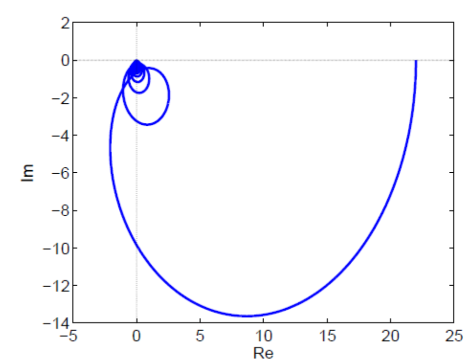




Technical Notes and Correspondence

Cascading With Inner Systems: Hankel Singular Values and Characteristic Values

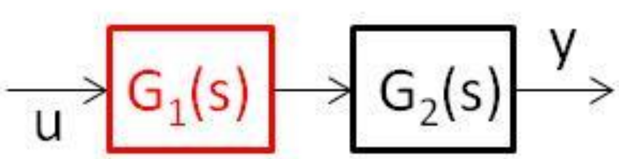
Arturo Buscarino, *Senior Member, IEEE*, Luigi Fortuna, *Fellow, IEEE*, Mattia Frasca, *Senior Member, IEEE*, and Giuseppe Nunnari, *Senior Member, IEEE*

***Abstract*—In this paper, new properties of the cascade between a multi-input multi-output linear time-invariant system, referred to in the following as the original system, and an inner system are dealt with. In particular, attention is devoted to the relationship between the Hankel singular values and characteristic values of the cascade system and those of the original one, proving that, if the inner system has gain greater than or equal to one, then the first n Hankel singular values (characteristic values) of the cascade system are greater than or equal to those of the original system. The results are then applied to derive a new property of minimum phase systems.**

***Index Terms*—All-pass systems, characteristic values, Hankel singular values, inner systems, linear time-invariant (LTI) systems.**

a procedure to obtain a minimal spectral factorization is presented, and in [10], which assesses a complete factorization theory of discrete-time all-pass functions. Recently, in [12], the framework was extended to linear stochastic models.

In this paper, we consider a multi-input multi-output (MIMO) LTI system of order n and connect it in cascade with an inner system of order n_1 and prove a property holding for both Hankel singular values and characteristic values: if the inner system has gain greater than or equal to one, then the Hankel singular values (characteristic values) of the cascade system of order $n + n_1$ are such that the first n Hankel singular values (characteristic values) are greater than or equal to those of the original system.



$$G_2(s)G_2^T(-s)=I$$

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Hankel singular values and LQG characteristic values of discrete-time linear systems in cascade with inner systems

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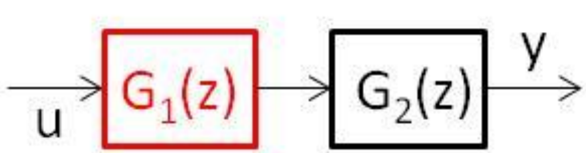
***Abstract*—Recent results have shown that, for continuous-time systems obtained by cascading an asymptotically stable system with an inner system, the first n Hankel singular values are greater than or equal to those of the original system. Similarly, cascading a system in minimal form with an inner system, the same property holds for the LQG characteristic values. In this technical note, we consider the discrete-time case and demonstrate that the property also holds for these systems. A very important consequence stemming from these results is that the Hankel singular values and the LQG characteristic values of input-delayed discrete systems are greater than or equal to those of their zero-delay counterpart.**

***Index Terms*—Discrete-time linear systems, all-pass systems, singular values, characteristic values, input-delay systems.**

important for singular filtering [10], [11], optimal LQ control [12] and in loop transfer recovery [13]. Factorization of rational discrete-time spectral densities has been approached in [8] and in companion papers [14], [15] by adopting strategies based on inner and all-pass functions.

The property discussed in [6] is proven for the continuous-time case; here, the discrete-time case is dealt with. More in detail, we consider a system formed by the cascade of a discrete-time MIMO linear, time-invariant (LTI) system of order n and an inner system of order n_1 and prove that, if the inner system has gain greater than or equal to one, then the Hankel singular values of the cascade system (which has order



$$G_2(z)G_2^T(1/z)=I$$

RISULTATI “*ESTIVI*” NON PUBBLICATI

1. Delay Independent Stability Control for Commensurate Multiple Time-Delay Systems

$$\dot{\mathrm{x}}(t) = \mathrm{A}_0\mathrm{x}(t) + \sum_{k=1}^{m} \mathrm{A}_k\mathrm{x}(t - r_k)$$

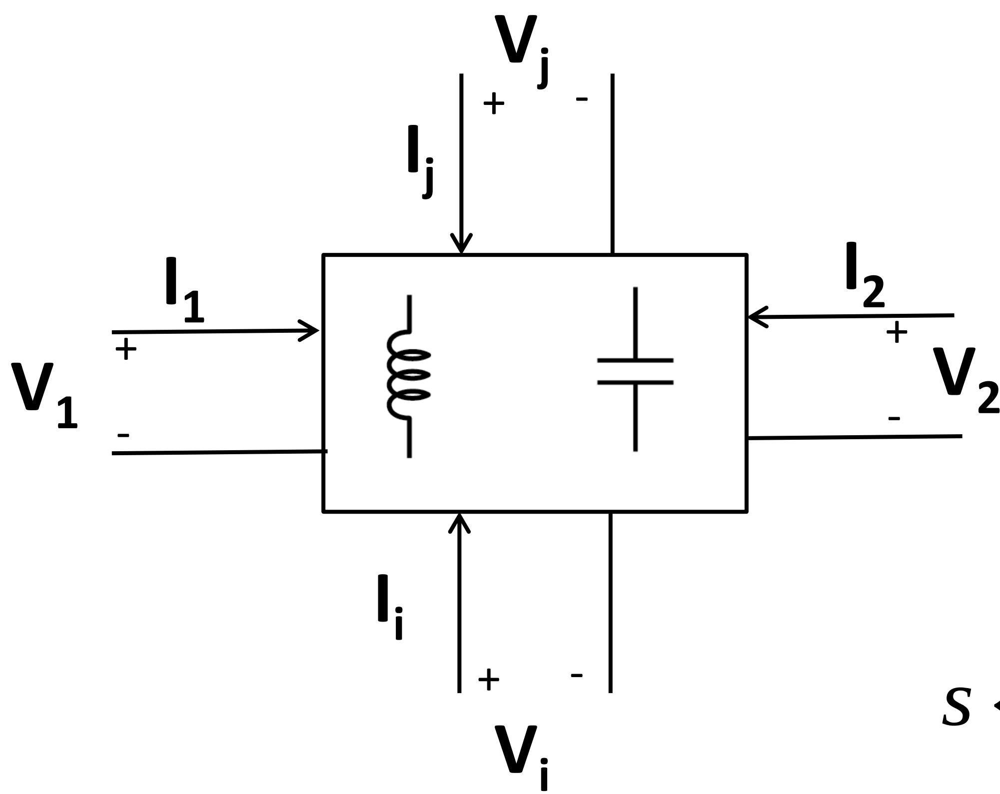
Is it possible to stabilize delay independently a Commensurate Multiple Time-Delay System, by using a single control parameter? YES (Proved)

$$\dot{\mathrm{x}}(t) = \bar{\mathrm{A}}_0\mathrm{x}(t) + \sum_{k=1}^{m} \mathrm{A}_k\mathrm{x}(t - k\tau)$$

where $\bar{\mathrm{A}}_0 = \mathrm{A}_0 - \mathrm{L}_0$ and $\mathrm{L}_0 = l\mathrm{I}$, with l being the scalar controller parameter gain and I is the identity matrix, is delay-independent stable.

RISULTATI “*ESTIVI*” NON PUBBLICATI

2. MIMO Frequency Transformations: all the previous results regarding the lossless transformations are valid if instead of being F(s) scalar, F(s) is a lossless MIMO function.



$$s \leftarrow F(s)$$

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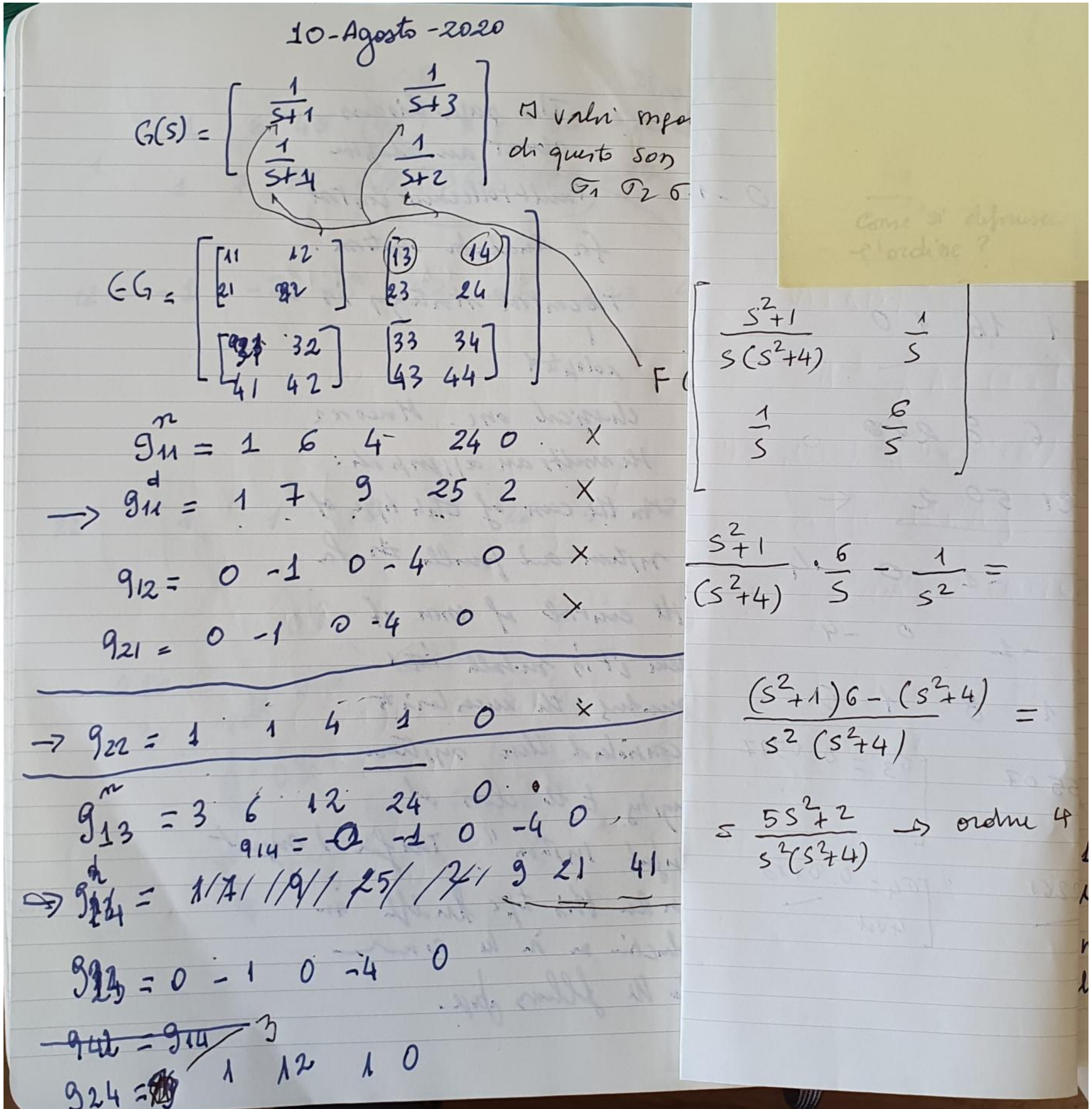

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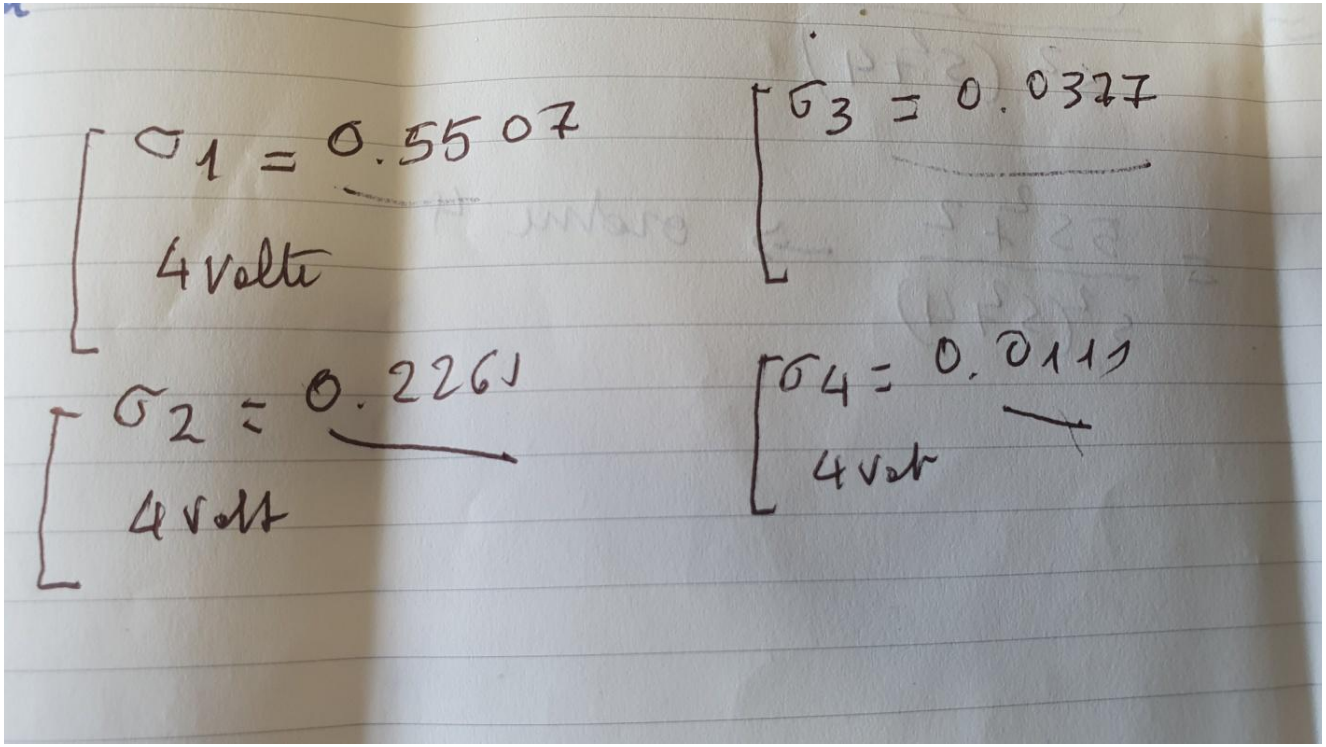

Valori singolari

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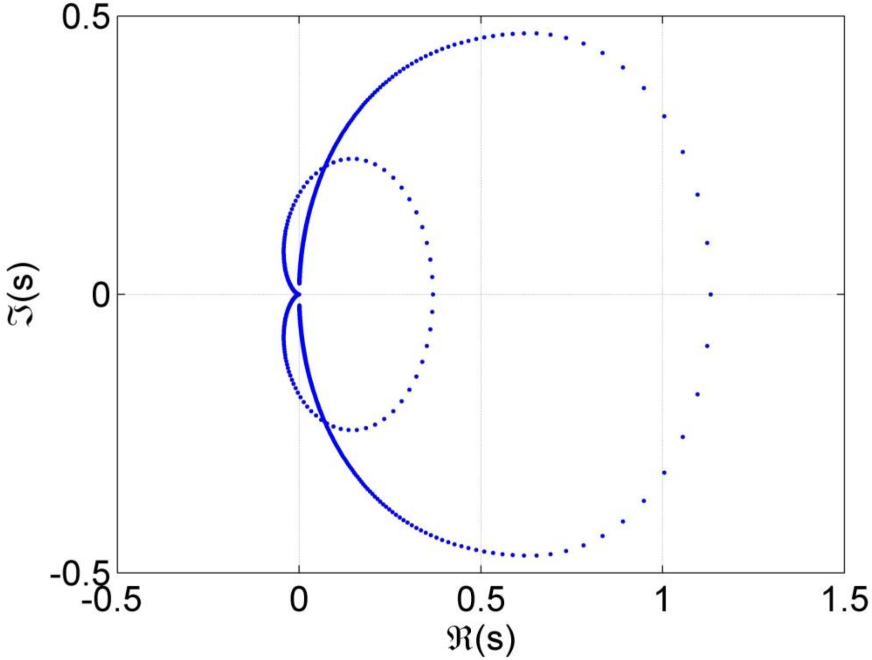

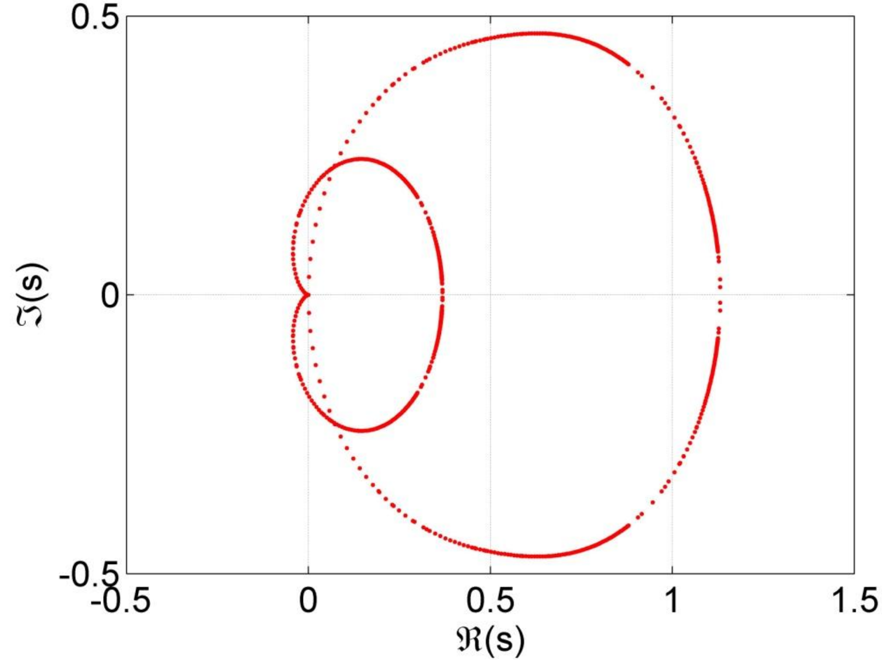

Diagrammi di Nyquist

G(s)

G(F(s))

CONSIDERAZIONI CONCLUSIVE

I risultati presentati fanno parte di uno spazio di ricerca che ci siamo riservati in parallelo ai progetti di ricerca finanziati a cui abbiamo dovuto far fronte nelle nostre attività accademiche.

Mantenere filoni di ricerca tradizionali significa non chiudere dei percorsi e rendere vivi quei filoni di studio che si andrebbero a spegnere negando così quasi tutto il lavoro di tante generazioni di ricercatori dell’Automatica.