

# REDUCTION OF LINEAR DYNAMIC SYSTEMS USING HANKEL NORM APPROXIMATION

Nidhi Singh\*

## Abstract

The Hankel norm approximation (HNA) method of model reduction often suffers from an inherent deficiency of showing errors in the step responses of original and reduced systems. A modified method of model order reduction for stable continuous linear time invariant systems is presented and is also extended to include discrete time systems. The objective of the reduction method, based on HNA, is to preserve the steady-state value of original system along with other important properties of the system. Bilinear transformation is used to transform the original system from  $s$ -domain to  $z$ -domain and vice versa. The method is illustrated by examples.

## Key Words

Hankel norm approximation, discrete systems, continuous systems, bilinear transformation, stability

## 1. Introduction

The need of replacing a high-order system by reduced model is motivated by computational and other practical advantages in synthesis, analysis and implementation. A large number of methods are available for simplified models of high-order systems. Most of the attention in the area of model reduction focuses on reduction of continuous time systems (CTSs) [1], [2]; however, the use of discrete time models is also very important for real-time systems. Many methods have been proposed, both in time and frequency domains. Each method has a different approach for the model reduction problem. Some are based on error minimization (ISE, IAE, etc.), eigenvalue preservation, time moment matching, and so on. Only some of them have been tried for discrete time systems (DTSs) [3]–[7]. It has been recognized that most of the concepts of CTS run parallel with DTS, and many CTS reduction methods have been extended to reduce the DTS. Although some direct methods in which reduction is carried out entirely in  $z$ -domain are developed [8], [9], the indirect methods in which bilinear transformation plays the key role are most

popular. In indirect methods, the DTS is transformed to equivalent CTS using linear transformation, bilinear transformation or homographic transformation [10]. The reduction is carried out in transformed domain and the reduced system is transformed back into  $z$ -domain using reverse transformation.

Among the various methods of model reduction, the most popular ones in time domain are balanced truncation method [11]–[13] and the optimal Hankel norm approximation (HNA) method [14]. Balanced truncation and HNA are built upon a family of ideas with very close connection to the singular value decomposition. These methods preserve stability and allow for global error bounds. One of the advantages of these techniques is that a *a priori* additive approximation error upper and lower bound can be obtained by using full-order system's Hankel singular values (HSVs) [15]. Hankel norm of a stable SISO system lies between the more conventional  $L_2$  and  $L_\infty$  norms [16]. The first stage in the HNA theory is the computation of a balanced realized model. This algorithm requires the original system to be completely observable and controllable [17]. HNA method has been extended to include certain classes of frequency weights [18] for scalar systems. This was further extended to the multivariable case [19].

The main purpose of this paper is to extend modified HNA method [20] for the reduction of DTSs using bilinear transformation. The step and frequency response of original and reduced-order model matches, which shows that the reduced-order model retains the important characteristics of original system.

## 2. Statement of the Problem

Let us consider a linear time invariant continuous system:

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx + Du\end{aligned}\tag{1}$$

where  $x \in R^n$ ,  $u \in R^m$ ,  $y \in R^p$  are the vectors of states, inputs and outputs, respectively. The matrices  $A \in R^{n \times n}$ ,  $B \in R^{n \times m}$ ,  $C \in R^{p \times n}$ ,  $D \in R^{p \times m}$  are assumed to be

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Recommended by Prof. C.W. De Silva  
(DOI: 10.2316/Journal.201.2013.4.201-2065)

# Hankel Norm Approximation For Infinitedimensional Systems Lecture Notes In Control Information Sciences

**LM Reder**



## **Hankel Norm Approximation For Infinitedimensional Systems Lecture Notes In Control Information Sciences:**

Hankel Norm Approximation for Infinite-Dimensional Systems A. Sasane, 2002-01-01 Model reduction is an important engineering problem in which one aims to replace an elaborate model by a simpler model without undue loss of accuracy The accuracy can be mathematically measured in several possible norms and the Hankel norm is one such The Hankel norm gives a meaningful notion of distance between two linear systems roughly speaking it is the induced norm of the operator that maps past inputs to future outputs It turns out that the engineering problem of model reduction in the Hankel norm is closely related to the mathematical problem of finding solutions to the sub optimal Nehari Takagi problem which is called the sub optimal Hankel norm approximation problem in this book Although the existence of a solution to the sub optimal Hankel norm approximation problem has been known since the 1970 s this book presents explicit solutions and in particular new formulae for several large classes of infinite dimensional systems for the first time *An Introduction to*

*Infinite-Dimensional Linear Systems Theory* Ruth F. Curtain, Hans Zwart, 2012-12-06 Infinite dimensional systems is now an established area of research Given the recent trend in systems theory and in applications towards a synthesis of time and frequency domain methods there is a need for an introductory text which treats both state space and frequency domain aspects in an integrated fashion The authors primary aim is to write an introductory textbook for a course on infinite dimensional linear systems An important consideration by the authors is that their book should be accessible to graduate engineers and mathematicians with a minimal background in functional analysis Consequently all the mathematical background is summarized in an extensive appendix For the majority of students this would be their only acquaintance with infinite dimensional systems Control of Uncertain Systems: Modelling, Approximation, and Design Bruce A.

Francis, 2006-03-07 This Festschrift contains a collection of articles by friends co authors colleagues and former Ph D students of Keith Glover Professor of Engineering at the University of Cambridge on the occasion of his sixtieth birthday Professor Glover s scientific work spans a wide variety of topics the main themes being system identification model reduction and approximation robust controller synthesis and control of aircraft and engines The articles in this volume are a tribute to Professor Glover s seminal work in these areas *Well-Posed Linear Systems* Olof J. Staffans, 2005-02-24 Publisher

Description **Modelling, Robustness and Sensitivity Reduction in Control Systems** Ruth F. Curtain, 2013-06-29 Historically one of the basic issues in control systems design has been robustness the ability of a controlled plant to withstand variations in or lack of knowledge of its dynamics Even if the dynamics of a system are accurately known for purposes of implementation it is often desirable to design a control system based on a simplified model Consequently it is essential to be able to guarantee a reasonable performance not only for the nominal plant but also for its neighbouring perturbations this is the issue of robustness Since the beginning of this decade major advances have been made in this area notably using the H approach this term is meant to cover the solution of sensitivity reduction approximation and model

reduction robustness and related control design problems using the mathematics of Hardy spaces and related areas in Harmonic Analysis This book contains the proceedings of the NATO Advanced Research Workshop on Modelling Robustness and Sensitivity Reduction in Control Systems which was held at the University of Groningen December 1986 Its aim was to explore the development of H design techniques and its ramifications in Systems Theory in a unified and systematic way with the emphasis on recent advances and future directions in this fast developing area In particular the following inter related aspects were addressed H mathematical foundations model approximation and robustness in control design optimal sensitivity reduction modelling and system identification and signal processing

**Identification of Nonlinear Systems Using Neural Networks and Polynomial Models** Andrzej Janczak, 2004-11-18 This monograph systematically presents the existing identification methods of nonlinear systems using the block oriented approach It surveys various known approaches to the identification of Wiener and Hammerstein systems which are applicable to both neural network and polynomial models The book gives a comparative study of their gradient approximation accuracy computational complexity and convergence rates and furthermore presents some new and original methods concerning the model parameter adjusting with gradient based techniques Identification of Nonlinear Systems Using Neural Networks and Polynomial Models is useful for researchers engineers and graduate students in nonlinear systems and neural network theory

**Operator Theory and Analysis** H. Bart, I. Gohberg, A.C.M. Ran, 2012-12-06 On November 12 14 1997 a workshop was held at the Vrije Universiteit Amsterdam on the occasion of the sixtieth birthday of M A Kaashoek The present volume contains the proceedings of this workshop The workshop was attended by 44 participants from all over the world participants came from Austria Belgium Canada Germany Ireland Israel Italy The Netherlands South Africa Switzerland Ukraine and the USA The atmosphere at the workshop was very warm and friendly There were 21 plenary lectures and each lecture was followed by a lively discussion The workshop was supported by the Vakgroep Wiskunde of the Vrije Universiteit the department of Mathematics and Computer Science of the Vrije Universiteit the Stichting VU Computer Science Mathematics Research Centre the Thomas Stieltjes Institute for Mathematics and the department of Economics of the Erasmus University Rotterdam The organizers would like to take this opportunity to express their gratitude for the support Without it the workshop would not have been so successful as it was Table of Contents Preface v Photograph of M A Kaashoek xiii Curriculum Vitae of M A Kaashoek xv List of Publications of M A Kaashoek xix I Gohberg Opening Address xxxi H Bart A C M Ran and H I Woerdeman Personal Reminiscences xxxv V Adamyan and R Mennicken On the Separation of Certain Spectral Components of Selfadjoint Operator Matrices 1 1 Introduction 1 2 Conditions for the Separation of Spectral Components 4 3 Example 9 References

**Advances in Communication Control Networks** Sophie Tarbouriech, Chaouki T. Abdallah, John Chiasson, 2004-09-22 The area of communication and computer networks has become a very active field of research by the control systems community in the last years Tools from convex optimization and control theory are playing increasing roles in efficient network utilization fair

resource allocation and communication delay accommodation and the field of Networked Control systems is fast becoming a mainstay of control systems research and applications This carefully edited book brings together solicited contributions from experts in the various areas of communication control networks referring to both networks under control control in networks as well as networked control systems control over networks The aim of this book is to reverse the trend of fragmentation and specialization in Communication Control Networks connecting various interdisciplinary research fields including control communication applied mathematics and computer science     *From Vector Spaces to Function Spaces* Yutaka

Yamamoto,2012-01-01 This book provides a treatment of analytical methods of applied mathematics It starts with a review of the basics of vector spaces and brings the reader to an advanced discussion of applied mathematics including the latest applications to systems and control theory The text is designed to be accessible to those not familiar with the material and useful to working scientists engineers and mathematics students The author provides the motivations of definitions and the ideas underlying proofs but does not sacrifice mathematical rigor *From Vector Spaces to Function Spaces* presents an easily accessible discussion of analytical methods of applied mathematics from vector spaces to distributions Fourier analysis and Hardy spaces with applications to system theory an introduction to modern functional analytic methods to better familiarize readers with basic methods and mathematical thinking and an understandable yet penetrating treatment of such modern methods and topics as function spaces and distributions Fourier and Laplace analyses and Hardy spaces     **From Data to**

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Chung,2004-01-23 Though PID control has a long history as much as its life force since Ziegler and Nichols published the empirical tuning rules in 1942 surprisingly it has never been changed in the structure itself The strength of PID control lies in the simplicity lucid meaning and clear effect Though it must be a widely cepted controller for mechanical control systems it is still short of theoretical bases e g optimality performance tuning rules automatic performance t ing method and output feedback PID control have not been clearly presented formechnicalcontrolsystems

Thesesubjectswillbethoroughlydiscussedin this book There are many books of PID controller for the purpose of process control but it is hard to nd a book on the characteristics of PID control for mechanical systems In the rst place when nonlinear optimal control theory is applied to mechanical systems a class of Hamilton Jacobi HJ equations is derived as a result of optimization There are two methods to solve a class of HJ eq tions a direct method using an approximation and inverse method nding the performance index from a class of HJ equations Also there are two control methods according to the objective the set point regulation control and t jectory tracking control The trajectory tracking control is basically di erent from set point regulation one in that the desired con guration velocity and acceleration pro les according to time progress are added to the motion of mechanical system This book is focusing on an inverse optimization method and the trajectory tracking control system Perturbation Compensator based Robust Tracking Control and State Estimation of Mechanical Systems SangJoo Kwon,Wan Kyun Chung,2004-07-07 This monograph investigates a practical way to achieve

robust motion control and state estimation Kalman filtering of mechanical systems which is a promising approach in terms of the perturbation compensator The book presents novel approaches for design and analysis of perturbation observers as well as an extension to robust motion control and robust state estimation The book is written in a self contained manner including experimental results in each chapter clearly validating the developed theories Optimal Control, Stabilization and Nonsmooth Analysis Marcio S. de Queiroz,Michael Malisoff,Peter Wolenski,2004-04-20 This edited book contains selected

papers presented at the Louisiana Conference on Mathematical Control Theory MCT 03 which brought together over 35 prominent world experts in mathematical control theory and its applications The book forms a well integrated exploration of those areas of mathematical control theory in which nonsmooth analysis is having a major impact These include necessary and sufficient conditions in optimal control Lyapunov characterizations of stability input to state stability the construction of feedback mechanisms viscosity solutions of Hamilton Jacobi equations invariance approximation theory impulsive systems computational issues for nonlinear systems and other topics of interest to mathematicians and control engineers The book has a strong interdisciplinary component and was designed to facilitate the interaction between leading mathematical experts in nonsmooth analysis and engineers who are increasingly using nonsmooth analytic tools **Theory of the**

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*Modeling and Analysis of Linear Hyperbolic Systems of Balance Laws* Krzysztof Bartecki,2015-12-21 This monograph focuses on the mathematical modeling of distributed parameter systems in which mass energy transport or wave propagation phenomena occur and which are described by partial differential equations of hyperbolic type The case of linear or linearized

2 x 2 hyperbolic systems of balance laws is considered i.e. systems described by two coupled linear partial differential equations with two variables representing physical quantities depending on both time and one dimensional spatial variable. Based on practical examples of a double pipe heat exchanger and a transportation pipeline two typical configurations of boundary input signals are analyzed: collocated wherein both signals affect the system at the same spatial point and anti collocated in which the input signals are applied to the two different end points of the system. The results of this book emerge from the practical experience of the author gained during his studies conducted in the experimental installation of a heat exchange center as well as from his research experience in the field of mathematical and computer modeling of dynamic systems. The book presents valuable results concerning their state space transfer function and time domain representations which can be useful both for the open loop analysis as well as for the closed loop design. The book is primarily intended to help professionals as well as undergraduate and postgraduate students involved in modeling and automatic control of dynamic systems.

Dynamics and Control of Large Structures Leonard Meirovitch, 1985



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<http://www.pet-memorial-markers.com/results/detail/Documents/guide%20to%20business%20records%20in%20the%20virginia%20state%20library%20and%20archives.pdf>

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