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HIERARCHICAL AGGREGATION OF LINEAR SYSTEMS WITH MULTIPLE TIME SCALES

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0. INTRODUCTION

Models of large scale systems typically include weak couplings between subsystems. This results in the evolution of different portions of the system at different time scales. Frequently, intuition suggests that subsystems or groups of states evolve slowly in comparison with their internal dynamics. This suggests that the overall system dynamics analysis may be simplified (or sometimes made tractable) by separately analyzing the dynamics at a specific time scale - by assuming constancy of variables evolving at slower time scales and steady state values for variables at faster time scales. If this intuition were to hold true, it then follows that system behavior may be approximated by means of a hierarchy of increasingly simplified models valid at progressively slower time scales. The motivation for the present work came from mathematical models for interconnected power systems. These models have variations on several time scales - nearly instantaneous adjustment of loadbus angles and voltages, dynamics of the swing equations, voltage regulator and turbine power generation dynamics, generation scheduling (set point changes) are examples of progressively slower dynamics.

With this general philosophy in mind, we study in [8], a very simple class of systems - linear and time invariant (equation 1.1). For this class of systems we model weak coupling by parametric dependence of (1.1) on ε, and obtain tight conditions under which a hierarchy of reduced order models valid at different time scales may be constructed. The study of this (deterministic) equation is also relevant to the hierarchical aggregation of finite state Markov processes with some rare transitions. The details of the application of our results in this context are presented in [3].

1. PROBLEM FORMULATION

We consider here linear time-invariant systems of the form

$$\dot{x}^{\varepsilon} = A_0(\varepsilon)x^{\varepsilon} \qquad x(0)=x_0 \tag{1.1}$$

where $x^{\varepsilon} \in R^n$ and the matrix $A_0(\varepsilon)$ is an analytic function of ε[†], of normal rank d except at $\varepsilon = 0$

$$A_0(\varepsilon) = \sum_{k=0}^{\infty} A_{0k}\varepsilon^k \tag{1.2}$$

we analyze the asymptotic behavior of $x^{\varepsilon}(t)$ as $\varepsilon \downarrow 0$ on the time interval $[0,\infty[$. In general

$$\lim_{\varepsilon\downarrow 0} \sup_{t\geq 0} ||x^{\varepsilon}(t)-x^{0}(t)||\neq 0$$

so that asymptotic behavior at several time scales needs to be considered - $x^{\varepsilon}(t)$ is said to have well defined behavior at time scale $t/g(\varepsilon)$ (where $g(\varepsilon)$ is a monotone increasing C^0 function on $[0,\varepsilon_0]$ with $g(0)=0$) if there exists a bounded continuous function $y_k(t)$, called the evolution at that time scale, such that

$$\lim_{\varepsilon\downarrow 0} \sup_{\delta<t\leq T} ||x^{\varepsilon}(t/g(\varepsilon))-y_k(t)||=0 \qquad \delta>0,\ T<\infty \tag{1.3}$$

In this paper we give tight sufficient conditions under which the multiple time scale behavior of $x^{\varepsilon}(t)$ can be fully described by its evolutions at time scales t/ε^k for integers $k=0,1,\ldots,m$. These evolutions are used to:

(i) provide a set of reduced order models valid at different time scales.

(ii) provide an asymptotic approximation to $x^{\varepsilon}(t)$ valid uniformly on $[0,\infty[$.

2. NOTATION

Given $A \in R^{n\times n}$, $R(A)$ and $N(A)$ denote the range and null space of A. $\rho(A)$ denotes the resolvent set of A, i.e. the set of $\lambda \in C$ such that the resolvent, denoted $R(\lambda,A) := (A-\lambda I)^{-1}$, is well defined.

If $\lambda=0$ is an eigenvalue of algebraic multiplicity m, then the Laurent series of $R(\lambda,A)$ at

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[†] Formally, our results hold even if $A_0(\varepsilon)$ is only assumed to have an asymptotic series (see, for eg. [4]) of the form (1.2), provided that $A_0(\varepsilon)$ has constant rank d for $\varepsilon\in]0,\varepsilon_0]$.

$\lambda=0$ has the form (see [5])

$$R(\lambda,A)=\frac{-P(A)}{\lambda}-\sum_{k=1}^{m-1}\lambda^{-k}D(A)^k+\sum_{k=0}^{\infty}\lambda^k S(A)^k \qquad (2.1)$$

where $P(A)$, the eigenprojection; $D(A)$, the eigen-nilpotent and $S(A)$ are defined by

$$P(A):=\frac{-1}{2\pi i}\int_\gamma R(\lambda,A)d\lambda \qquad (2.2)$$

$$D(A):=\frac{-1}{2\pi i}\int_\gamma \lambda R(\lambda,A)d\lambda \qquad (2.3)$$

$$S(A):=\frac{-1}{2\pi i}\int_\gamma \lambda^{-1}R(\lambda,A)d\lambda \qquad (2.4)$$

with γ a positively oriented closed contour enclosing 0 but no other eigenvalue of A.

A is said to have semi-simple null structure (SNS) if $D(A)=0$. In that case, $R^n = \mathcal{R}(A) \oplus \mathcal{N}(A)$ and $P(A)$ is the projection onto $\mathcal{N}(A)$ along $\mathcal{R}(A)$. A is said to be semi-stable if it has SNA and all its non-zero eigenvalues are in the open left half plane.

If A is semistable, then $\lim_{t\to\infty} e^{At}=P(A)$ and further

$$S(A)=-\int_0^\infty (e^{At}-P(A))dt=(A+P(A))^{-1}-P(A).$$

Since $S(A)$ is a generalized inverse of A $S(A)Ax = x = AS(A)x$ for all $x \in \mathcal{R}(A)$) we denote it $A^{\dagger}$.

3. STATEMENT OF MAIN RESULT

We present here a uniform (in t) asymptotic approximation of $e^{A_0(\varepsilon)t}$ involving behavior at time scales t/ε^k ; $k=0,1,\ldots,m$. The proof relies on results in [5] and is given in [8]

For our development, we need an array of matrices A_{ik}, $i\geq 0$, $k\geq 0$ starting from the A_{0k} of (1.2), constructed recursively ((k+1)th row from kth row) by the following formula

$$A_{k+1,\ell}=-\sum_{p=1}^{\ell+1}(-1)^p \sum_{\substack{\nu_1+\ldots+\nu_p=\ell+1\\ k_1+\ldots+k_{p+1}=p-1\\ \nu_i\geq 1,\ k_i\geq 0}} S_k^{(k_1)}A_{k\,\nu_1}S_k^{(k_2)}\cdots A_{k\,\nu_p}S_k^{(k_{p+1})}$$

where $S_k^{(0)}=-P(A_{k,0})$ and $S_k^{(k_i)}=(A_{k,0}^{\dagger})^{(k_i)}$.

Remarks: (i) The computation of $A_{k+1,\ell}$ requires only $A_{k,0},A_{k,1},\ldots,A_{k,\ell+1}$ so that it proceeds triangularly as shown in Table 1.

(ii) of special interest to us in the sequel is the structure of $A_{00},A_{10},A_{20},\ldots,$ since they determine the leading term in the asymptotic expansion of $e^{A_0(\varepsilon)t}$. For these matrices, (3.1) can be simplified considerably. (see Remark (ii) after the Theorem and Corollary).

Theorem

Let $A_0(\varepsilon)$ be a marrix with SNS of the form (1.2) of normal rank d except at $\varepsilon=0$. If $A_{00},A_{10},\ldots A_{m0}$ are semistable with rank A_{00} + rank $A_{10}+\ldots+$ rank $A_{m0}=d$ then

$$R^n = \mathcal{R}(A_{00}) \oplus \cdots \oplus \mathcal{R}(A_{m0}) \oplus \mathcal{N} \qquad (3.2)$$

where $\mathcal{N}=\bigcap_{k=0}^{m}\mathcal{N}(A_{k0})$.

Further let P_k, for $k=0,1,\ldots,m$, be the projection onto $\mathcal{N}(A_{k0})$ defined by (2.2) and $Q_k = I-P_k$.

Then

$$\lim_{\varepsilon\downarrow 0}\sup_{t\geq 0}\left\|e^{A_0(\varepsilon)t}-\phi(\varepsilon,t)\right\|=0 \qquad (3.3)$$

where $\phi(\varepsilon,t)$ is any one of the four expressions below

$$\sum_{k=0}^{m} e^{A_{k0}\varepsilon^k t}Q_k + P_0P_1\cdots P_m \qquad (3.4)$$

$$\sum_{k=0}^{m} e^{A_{k0}\varepsilon^k t} - mI \qquad (3.5)$$

$$\prod_{k=0}^{m} e^{A_{k0}\varepsilon^k t} \qquad (3.6)$$

$$e^{\sum_{k=0}^{m} A_{k0}\varepsilon^k t} \qquad (3.7)$$

□

With this theorem in hand, the entire multiple time-scale structure of (1.1) can be read off as follows:

Corollary

Under the conditions of Theorem 1, $x^{\varepsilon}(t)$ of (1.1) has the following multiple-time scale properties:

$$\text{(i)}\quad \lim_{\varepsilon\downarrow 0}\ \sup_{0<\delta\le t\le T<\infty} \left\| x^{\varepsilon}(t/\varepsilon^{k}) - \pi_k\, e^{A_{k0}t} x_0 \right\| = 0 \tag{3.8}$$

for $\delta>0$, $T<\infty$ and $k=0,1,\dots,m-1$

$$\text{(ii)}\quad \lim_{\varepsilon\downarrow 0}\ \sup_{0<\delta\le t<\infty} \left\| x^{\varepsilon}(t/\varepsilon^{m}) - \pi_m\, e^{A_{m0}t} x_0 \right\| = 0 \tag{3.9}$$

for $\delta>0$

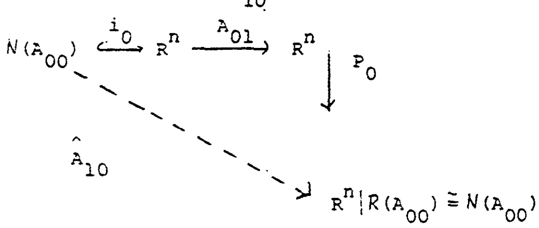
where $\pi_0=1$ and $\pi_k=P_0P_1\cdots P_{k-1}$ for $k=1,\dots,m$.

Equation (3.8) implies the results of [1] and [2] where the authors analyzed the convergence $A_0(\varepsilon)t/\varepsilon^{s}$ for fixed s and over compact time intervals of the form $[0,T]$.

Remarks: (1) The requirement of semi-stability of the matrices $A_{00},A_{10},\dots,A_{m0}$ to obtain well defined behavior at time scales t/ε^{k} is a tight sufficient condition. Examples showing the failure of the theorem without these assumptions, are given in Section 4.

(ii) It is important to be able to calculate the A_{k0} for $k=0,1,\dots,m$ for the given data A_{00},A_{01} $A_{02},\dots$ of (1.2), without having to obtain the complete matrix of Table 1. This can be done by a variety of methods. One approach that is successful is the formal asymptotics of [7] relating the A_{k0} to Toeplitz matrices constructed with the $\{A_{0i}\}_{i=0}^{\infty}$. Connection is made therein with the Smith McMillan zero of $A_0(\varepsilon)$ at $\varepsilon=0$. In particular m is proven to be the order of the Smith McMillan zero of $A_0(\varepsilon)$ at $\varepsilon=0$. The construction of the A_{k0} from the A_{0i} proceeds as follows:

A_{10} is the null extension to R^n of A_{01} mod $R(A_{00})/N(A_{00})$, i.e. $A_{10}=P_0A_{01}P_0$, where P_0 is defined in the theorem. Pictorially A_{10} is the null extension to R^n of $\hat{A}_{10}$ obtained as below



(here, i_0 is inclusion)

A_{20} is the null extension to R^n of

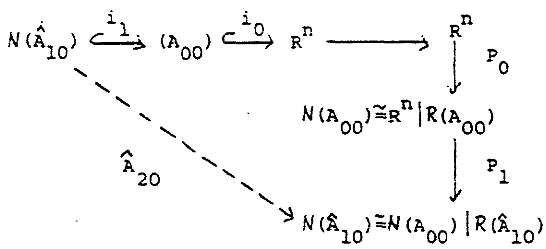
$A_{02}-A_{01}A_{00}^{\dagger}A_{01}$ mod $R(A_{00})$ mod $R(\hat{A}_{10})\,|\,N(\hat{A}_{10})$,

i.e., A_{20} is given by

$$P_1P_0(A_{02}-A_{01}A_{00}^{\dagger}A_{01})P_0P_1\ :$$

where P_1 is defined as in the theorem Pictorially, A_{20} is the null extension to R^n of $\hat{A}^{20}$

$$A_{02}-A_{01}A_{00}^{\dagger}A_{01}$$



and so on. The reader may refer to [7] for complete proof and details as well as the connections between $A_{10},A_{20},A_{30},\dots$ and the Toeplitz matrices

$$\begin{bmatrix} A_{01} & A_{00} \\ A_{00} & 0 \end{bmatrix},\quad \begin{bmatrix} A_{20} & A_{10} & A_{00} \\ A_{01} & A_{00} & 0 \\ A_{00} & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} A_{03} & A_{02} & A_{01} & A_{00} \\ A_{02} & A_{01} & A_{00} & 0 \\ A_{01} & A_{00} & 0 & 0 \\ A_{00} & 0 & 0 & 0 \end{bmatrix}$$

and so on.

(iii) The reader should observe using the formulae in remark (ii) above that even if $A_0(\varepsilon)=A_{00}+\varepsilon A_{01}$ the system can exhibit time scales of order t/ε^{2}, t/ε^{3} and so on. This is not a widely appreciated fact.

(iv) Reduced order models. It follows from (3.8) and (3.9) that the evolution of $x^{\varepsilon}(t)$ at time scales t/ε^{k}, $k=0,1,\dots,m$ is given by

$$y_k(t) = e^{A_{k0}t}\,\pi_k x_0 \qquad k=0,1,\dots,m$$

Thus, $x^{\varepsilon}(t)$ may be represented asymptotically by the following expression uniformly valid for $t\ge 0$.

$$x^{\varepsilon}(t) = \sum_{k=0}^{m} y_k(\varepsilon^{k}t) + \Big(I-\sum_{k=0}^{m}\pi_k\Big) + o(1)$$

From the direct sum decomposition (3.2) of the theorem, it is clear that a basis $T \in R^{nxn}$ can be chosen such that

$$e^{A_0(\varepsilon)t} = T \begin{bmatrix} I & e^{\tilde{A}_m \varepsilon^m t} & & & \\ & & \ddots & & \\ & & & e^{\tilde{A}_1 \varepsilon t} & \\ 0 & & & & e^{\tilde{A}_0 t} \end{bmatrix} T^{-1} + (1) \qquad (3.10)$$

where $\tilde{A}_0,\ldots,\tilde{A}_m$ are full rank square matrices representing the non zero portions of $A_{00},\ldots,A_{m0}$ in the new basis. (3.10) shows that the system (1.1) decouples asymptotically into a set of subsystems evolving at different time scales governed by the reduced order dynamics of $\{\tilde{A}_k\}_{k=0}^m$.

(v) Two time scale systems have been the focus of considerable effort by Kokotovic and coworkers (see [6], for example). It is easy to check in our framework that the assumptions in their systems guarantee precisely two time scales.

(vi) The significance of each row of matrices in Table 1 is discussed in [8].

4. TIGHTNESS OF THE SEMI-STABILITY CONDITION

The requirement of semi-stability for the matrices $A_{00}, A_{10},\ldots,A_{m0}$ for the system (1.1) to have well defined behavior at time scales $t, t/\varepsilon,\ldots,t/\varepsilon^m$ is tight. Counterexamples can be found for the nonexistence of well defined behavior at different time scales if A_{k0} is not semi-stable for some k:

Counterexample 1 (A_{00} does not have SNS)

Let $A_0(\varepsilon) = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} - \varepsilon \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$

Then,

$$e^{A_0(\varepsilon)t} = \begin{bmatrix} \cos\sqrt{\varepsilon}\, t & -\sqrt{\varepsilon}\sin\sqrt{\varepsilon}\, t \\ \frac{1}{\varepsilon}\sin\sqrt{\varepsilon}\, t & \cos\sqrt{\varepsilon}\, t \end{bmatrix} e^{-\varepsilon t}$$

Note that $\lim_{\varepsilon\downarrow 0} e^{A_0(\varepsilon)t/\varepsilon}$ does not exist for any t showing lack of well defined behavior at time scale t/ε.

Remark: Recall that A_{k0} is semistable if it has SNS and all non zero eigenvalues have negative real parts. The necessity of the second condition is obvious and we will not furnish a counterexample to illustrate it. We would like to note that the semistability of $A_0(\varepsilon)$ for $\varepsilon \in [0,\varepsilon_0]$ does not imply the semistability of $\{A_{k0}\}_{k=1}^m$.

Counterexample 2 (Semistability of $A_0(\varepsilon) \not\Rightarrow$ semistability of A_{k0})

Let

$$A_0(\varepsilon) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 1 & -2 \end{bmatrix} + \varepsilon \begin{bmatrix} 1 & 0 & -2 \\ 1 & 1 & -2 \\ 0 & 0 & 0 \end{bmatrix}$$

Note that the eigenvalues of $A_0(\varepsilon)$ are 0, $-2+o(1)$, $-\varepsilon^2+o(\varepsilon^2)$, showing the semi-stability of $A_0(\varepsilon)$. It may further be verified that

$$A_{10} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 0 \\ 0 & -1/2 & 0 \end{bmatrix}$$

so that A_{10} is nilpotent. In this example

$\lim_{\varepsilon\downarrow 0} e^{A_0(\varepsilon)t/\varepsilon^2}$ does not exist showing no well-defined behavior at time scale t/ε^2 in spite of a real eigenvalue of order ε^2.

5. CONCLUSIONS

Our theorem in section 3 provides a uniform approximation over the entire real line $[0,\infty)$ to the evolution of the system (1.1), thereby extending the results of [1], which are valid only for intervals of the form $[0,T/\varepsilon]$. Furthermore, the hierarchy of models which result from the Corollary is an extension to multiple time scales, of the aggregation results in [6]. The application of these approximations to problems of estimation and control, are currently under study, and will be reported in later publications.

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A_{00}	A_{01}	$A_{0\ell}$
A_{10}	A_{11}	$A_{1,\ell-1}$
⋮	⋮	
$A_{\ell-1,0}$	$A_{\ell-1,1}$	
$A_{\ell,0}$		

Table 1: The array $A_{k,\ell}$ is grown triangularly.