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A Hierarchy for Modeling High Speed Propulsion Systems

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Overview

This is the final report for NASA Grant NAG 3-904, Reduced Order Propulsion Models for Control System Design. It is meant to be an overview of the general research effort for the last five years. Much of the earlier research is discussed in an interim report submitted in September, 1990, which is available from the authors, or from the NASA Lewis Grant Coordinator, Kevin Melcher. This report is broken into several tabbed sections. Section 1 will be a general discussion of the modeling problem and is intended to stand alone. Section 2 is a comprehensive list of papers, theses, and other results generated by this grant. It also includes on-going projects that will be provided to the Grant Coordinator upon completion. The remaining sections contain copies of new papers that are not included in the previous interim report.

Section 0. Introduction

Methods for modeling high speed propulsion systems will be discussed. Included in this category are internal flow propulsion systems that do not contain rotating machinery. Specifically, inlets, ramjets, and scramjets are considered. Some direct extensions to rotating machinery are available, however they are not discussed. It should be stressed here, that the main application of the resulting models is some aspect of control system design. This then requires a clear understanding of the trade-offs between model complexity, to correctly model the system, and model simplicity, to allow control system design. This report then clarifies the modeling assumptions that are necessary for various levels of model complexity.

Gasdynamic flows are usually described by the set of Euler equations (see the next page or [Hirsch; Anderson, Tannehill, & Pletcher]). As internal flows are the primary consideration, a quasi-one-dimensional approximation is often satisfactory and is pursued here. Very high speed flows sometimes require the inclusion of viscosity effects, temperature dependent gases, and chemical reactions. Temperature dependent gases are easily accounted for in the quasi-one-dimensional Euler equations by allowing the particular ratio of specific heat to be a function of temperature [Anderson; Ames Tables]. Viscosity effects require the addition of an extra term to the momentum equation of the Euler equations to change them into the Navier-Stokes equations [Anderson, Tannehill, & Pletcher]. This extra term is easily accounted for by all of the methods discussed, as long as two dimensional effects such as boundary layers and turbulence are not considered [Lin]. Chemically reacting gases are more of a problem, as each chemical species requires the addition of another continuity equation, as well as diffusion, energy release, and reaction rate terms to the Euler equations [Oran & Boris]. Furthermore, [Anderson] shows that hydrogen in air requires seven species and possibly 140 reactions. Although this is important, the increased complexity will not be considered practical at this time. Chemical reactions can be accounted for by the addition of heat in the energy equation for the present. Clearly the addition of all these effects into either a nonlinear or linearized model is an important area for future research. Other important phenomena that will not be discussed here are boundary layers, turbulence, oblique shocks, inlet buzz, and combustion instabilities. These phenomena require at least two space dimensions for an

accurate and physically realistic representation [Hsieh, Wardlaw, & Collins; Lin]. Extending the discussion contained here to these higher dimensional phenomena is of great future importance.

The quasi-one-dimensional Euler equations are [Varner et al (LAPIN Report)]

$$\text{continuity} \quad \frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho u A)}{\partial x} = M$$

$$\text{momentum} \quad \frac{\partial(\rho u A)}{\partial t} + \frac{\partial[A(p + \rho u^2)]}{\partial x} = p \frac{\partial A}{\partial x} + F$$

$$\text{energy} \quad \frac{\partial(EA)}{\partial t} + \frac{\partial[Au(E+p)]}{\partial x} = -p \frac{\partial A}{\partial t} + Q$$

where $p = \rho RT = (\gamma - 1)[E - 0.5\rho u^2]$; $E = \rho[c_v T + 0.5u^2]$; $\gamma = \frac{c_p}{c_v}$; and the other variables have their usual definitions [Varner et al (LAPIN Report)]. The solution of these equations with various levels of complexity is the purpose of the following discussion. As mentioned earlier, many high speed propulsion systems can be approximately represented by these equations.

The discussion which follows is separated into four areas. These are in order of discussion; 1) CFD models that represent the entire nonlinear system, or high order nonlinear models; 2) high order linearized models derived from the fundamental physics; 3) low order linear models obtained from the other high order models; and 4) low order nonlinear models (order here refers to the number of dynamic states). Included in the discussions on modeling will be any special considerations based on the relevant control system designs. Where necessary, some digression into specialized control techniques will also be undertaken.

Section 1. High Order Nonlinear Models

This section considers nonlinear models that contain large numbers of states and are often very accurate. Most of these methods are based on computational fluid dynamics (CFD) and are typically finite difference representations of the quasi-one-dimensional Euler equations above. These methods are further divided into methods of high, medium, and low accuracy.

High Accuracy Methods

The methods considered to be highly accurate are usually implicit methods [Varner et al (LAPIN Report); Hirsch; Anderson et al]. They consider more than one space dimension and can have millions of spatial lumps, and thus millions of states. Although these methods are perhaps not practical for control system design, or real-time simulation, they do provide a very good representation of the system dynamics. Currently, methods of this type will require hours, or even days, of computing time to provide a complete transient response. In the near future, however, increased computational speed could allow real-time CFD models to be running in parallel with actual high speed propulsion systems. With appropriately placed sensors, the real-time CFD model would function as an observer, providing a control algorithm with information about all the flow parameters everywhere in space. This will then push the control system designer to find a way of incorporating all this information into a control system. The question being, "if we have all this information about all the states of the flow, everywhere, what then do we do with it in order to provide an improved control system design." This question has been considered in [Hartley & Xia] where distributed functional observers and controllers are shown to obey a separation principle. This problem will also be discussed in Section 2.

Medium Accuracy Methods

Medium accuracy methods are in many ways more practical than the high accuracy methods discussed above. They use the quasi-one-dimensional Euler equations and finite difference schemes that have a local truncation error proportional to the timestep squared and/or the spacestep squared, and are thus second order accurate. These methods typically contain

hundreds of states and are thus somewhat more tractable and manageable. The method of choice in this category is clearly MacCormack's method [Hirsch; Anderson, Tannehill, & Pletcher; Hartley, Melcher, & Bruton], or any of the other variations on the two-step Lax-Wendroff idea. This method uses a predictor-corrector approach where an approximate solution is predicted in a downstream fashion, and the improved solution is corrected in an upstream fashion. The reader is reminded that the main difficulty in simulating the quasi-one-dimensional Euler equations is the first spatial derivative appearing there. The finite difference replacement must allow information to travel in both directions. The naive choice of either forward or backward differences does not allow this simultaneously. The next obvious idea of using central differences is unfortunately unstable. Thus one is left to be clever. The medium accuracy clever solution is the family of two step Lax-Wendroff methods [Hirsch; Peyret & Taylor].

MacCormack's method has been very useful in modeling the Euler equations. It has been used to model various propulsion system components [Varner et al (LAPIN Report); Hartley, Melcher, & Bruton]. The user is reminded that smoothing is required after the predict-correct mode in order to reduce the spatial oscillations due to the shock discontinuity [Interim report].

Low Accuracy Methods

Here low accuracy will refer to methods that have a local truncation error on the order of the timestep or spacestep size, or first order accurate methods. The most common methods in this category are the flux splitting methods [Anderson, Tannehill, & Pletcher; Hirsch]. There are several variations of these methods, based on the particular local splitting method, but the general idea is that somehow the flow at a given lump is separated into that which is traveling upstream and that which is traveling downstream. Once this is done, backward differences can be used on that which is traveling downstream and forward differences can be used on that which is traveling upstream. This then preserves accuracy, stability, and shock capturing while still only using first differences. In real-time simulation, these splitting methods are no faster than MacCormack's method, due to the necessity to separate the flows at

each lump on each timestep. Even with pre-separated methods, multiple function evaluations are still necessary and thus little speed is gained.

An alternative to these splitting methods is termed physical lumping. Here, the spatial differencing of each term in the given derivative is done in a physically intuitive sense. This is discussed in more detail in [Immel, Hartley, & DeAbreu]. Although mentioned in [Roache] and attributed to [Courant, Isaacson, & Rees], the approach has received little attention in the CFD community. This is probably due to the difficulty associated with predicting accuracy and stability. However [Immel, Hartley, & DeAbreu] have shown that reasonable accuracy and shock capturing are possible in a supersonic inlet model. More study should be given to this approach as it provides a relatively simple and inexpensive method for simulating the quasi-one-dimensional Euler equations. Note that both the splitting methods and the physical lumping methods also require hundreds of states, as did the medium accuracy methods.

Section 2. High Order Linear Models

Where the accurate large perturbation models of the last section are important for control evaluation; small perturbation, or linearized, models are usually required for control design. The next two sections of this document will address techniques for obtaining linearized models of the given Euler equation flowfield. This section will address techniques for obtaining linear models with a large number of dynamic states, usually based on physical first principles. Section 3 will address how to reduce the size of these to something that is more reasonable for control design. The three basic methods discussed in this section are the approximate linear solution of the exact nonlinear system, exact solution of an approximate linear system, and approximate solution of an approximate linear system. All of these methods first require the particular system to approach the desired steady state. Once the steady state solution is obtained, a linear model which is only valid for small perturbations from this operating point can be created.

CFD Based Methods

CFD based methods provide good nonlinear models for the Euler equations. Fortunately, the flux splitting methods also allow a simple linearization technique to be used to create a high order linear approximation to the Euler equations. This method again requires the steady state conditions of the flowfield. Once these are obtained, either computationally or analytically from the design specifications, the desired number of spatial lumps must be determined. Usually the number of spatial lumps is determined from the desired spatial accuracy and the length of the flowfield. Given this, a particular CFD method is selected. The flux splitting methods are particularly suited to this approach. Mathematically combining the CFD method with the Euler equations and linearizing, allows the construction of a block tridiagonal system matrix, with the number of states equal to three times the number of lumps. Clearly, to obtain reasonable spatial accuracy requires a large number of lumps, perhaps hundreds. This approach, using one of the split flux methods, is discussed more completely in [Chicatelli; Chicatelli & Hartley]. It is discussed using the physical lumping method in [Immel, Hartley, & DeAbreu].

Exact Solution of the Linear Flowfield

Since most propulsion systems have variable cross-sections, the properties of the flow depend upon spatial position. A linear approximation to the Euler equations themselves then requires some additional assumptions. Either many linear lumped volumes must be used and pasted together, or a single linear lumped volume can be used with volume averaged flow properties, or the linear flowfield must be solved with spatially dependent flow properties. The latter is extremely difficult to do generally and is not considered further. The second must be done before the first, so the second will be considered first in this subsection. This is essentially obtaining an exact solution to an approximate problem.

To use this approach, the volume averaged steady state solution must be found for the entire flowfield, which is considered to be one lump. Then, the linearized flowfield is described by a linearized set of the Euler equations, with the appropriate boundary conditions,

inputs, outputs, and shock discontinuities also linearized. The resulting system can then be Laplace transformed and the resulting spatial boundary value problem can be solved, letting the Laplace s-variable be a constant. The end product of this procedure is then a non-rational meromorphic transfer function (or transfer matrix) which basically has an infinite number of states. When done correctly, this transfer function represents the Laplace transform of the Green's function of the flowfield and is very useful for studying the input-output properties of the system [see Butkovskii for more general information on this approach]. This approach has been effectively applied to the isentropic subsonic flow problem (a modeling assumption that eliminates the energy, or entropy, equation in the Euler equations) with the results presented in [Sarantopoulos & Hartley]. This same procedure is currently being expanded to consider supersonic-subsonic combination flows, supersonic flows with detonation, and multiple lumps pasted together [Sarantopoulos].

Approximate Solution to the Linear Flowfield

This approach basically follows that above, but the meromorphic transfer functions are not obtained in the process. Before the algebra is performed, the flow is diagonalized, as in flux splitting, and the resulting conservative information delays (transport lags) are replaced by Pade approximations. This is the method of [Willoh; Cole & Willoh] and has been used extensively. Since the meromorphic time delays have been replaced by finite order Pade approximations, the resulting number of states is equal to $3 \times (\text{number of lumps}) \times (\text{Pade order}) + 1$. Another method that has been used, and is apparently more accurate and appropriate, is to replace the time delays by discrete delays (z-inverses) in a digital simulation of the entire system [Hartley]. Note that the general Cole-Willoh approach does not contain the spatial input-output information of the Sarantopoulos approach above. Although certainly useful, it would probably be more accurate to approximate the entire Sarantopoulos transfer function than to approximate little pieces of the entire transfer function and then multiply them together as in the Cole-Willoh approach.

Section 3. Low Order Linear Models

Based on the methods of the previous section, several model reduction approaches are possible. These are discussed first in this section. Following this, some other approaches for generating low order linear models are presented.

Reduction of Linearized CFD Models

The linearized state space models based on the CFD approach discussed in the last section are very well suited to the wide variety of modern linear model reduction techniques based on balancing [Moore; Laub, Heath, Paige, & Ward; Safanov & Chiang]. These techniques have been applied to both the split flux and the physical lumping approaches with considerable success using the MATLAB 'schmr' function. An 80-90% reduction of states has been possible in supersonic inlet models as well as ramjets models with upstream, downstream, and mid-stream inputs [Chicatelli; Chicatelli & Hartley; Immel, Hartley, & DeAbreu]. Essentially, many states are only slightly observable/controllable. This is particularly true for the supersonic part of the flow with an input in the subsonic region. Clearly, the states in the supersonic region should not be controllable from downstream. Furthermore, there is some tendency to lose controllability/observability based on the particular positions chosen for the actuators and the sensors. These isolated state problems must be more clearly understood before real-time CFD observers can be effectively implemented. To this end, an input-output separation principle for observing and controlling spatially distributed systems has been developed and studied in [Hartley & Xia].

Direct Reduction of Meromorphic Transfer Functions

The idea here is to obtain some finite order system based on the Sarantopoulos-Green's transfer function approach discussed in the last major section. This was already introduced via the Cole-Willoh approach where the lump time delays were replaced by either Pade approximations or discrete-time delays. The idea here will be to replace the entire transfer function by an approximation. Several methods are available for approximating general

meromorphic transfer functions. Some of the more common methods are truncated Taylor series approximations of the entire transfer function (effectively a Pade approximation of the meromorphic function and not necessarily stable [Edrei, Saff, & Varga]), truncated Taylor series expansions of the numerator and denominator separately (only stable if done carefully with positive exponential powers rather than negative powers), infinite product expansions (if the transfer function is a simple function), and partial fraction expansions (only if enough approximate pole positions can be found). More information on all these methods can be found in [Henrici]. An alternative to this approach that has only recently been developed is based on approximation of the system Hankel operator [Partington]. This method is generally very difficult and requires knowledge of the system impulse response. An approximation of this method has been applied to representative inlet systems in [Hartley & DeAbreu] using a numerical inverse Laplace transform. Another approximation has been presented by [Gu & Khargonekhar, & Lee] which directly uses an inverse Fourier transform.

Optimized Low Order Models

The idea here is to optimally choose the parameters of a given reduced order model by reducing some performance measure. This is fairly simple conceptually, and many useful performance measures are available. If a time response is available, either from the transfer function or from time response data, a time domain performance measure, such as squared error or time weighted squared error can be used. This can be also considered an input-output identification method. An exhaustive study using this approach can be found in [Piercy] where it is shown that the batch total least squares method is somewhat more robust and accurate than the usual batch least squares method when applied to a supersonic inlet problem. Alternatively, if only the transfer function is available, minimization of some performance measure in the frequency domain is possible. The reader is reminded that this is not usually a linear problem and can have many local minima. This approach has been used to reduce the order of a representative inlet system in [Dariush & Hartley].

Other Methods for Generating Low Order Models

Obviously other methods are available for generating linear low order models of high

speed propulsion systems. These are reviewed more completely in [Hartley]. One approach worth mentioning is that of representing the Euler equations by several lumped circuit equivalents [Stalzer & Fiedler]. If an isentropic equivalent is used, the usual transmission line equations result. Otherwise another parallel voltage path is required for the third Euler equation. This circuit approach allows for quick analysis and testing on the currently available circuit analysis packages, such as SPICE.

Section 4. Low Order Nonlinear Models

Although there are many model reduction methods available for linear systems, unfortunately there are very few available for nonlinear systems. Hence it is generally difficult to start with the CFD models of Section 1 and obtain reasonably accurate, low order, large perturbation nonlinear models. This method is somewhat simplified for low speed subsonic flow where a variety of physical lumping methods have been used [Hartley; Krosel & Bruton; Colbourne]. It is also fairly simple for high speed supersonic flow [Interim Report: Chicatelli Scramjet]. Unfortunately, the inclusion of shock dynamics makes this problem much more difficult. The problem with the usual model reduction methods, and low order physical lumping methods, is that the states in a nonlinear finite difference CFD model are not always readily available in a closed form (such as MacCormack's method), and when they are (as in physical lumping) they each represent information in a given point in space. When the shock undergoes a large perturbation, it is not intuitively clear to individuals, or the reduction method, which combinations of states are important. Currently, research is continuing in this effort using the physical lumping models as they allow easy access to the states.

The creation of single closed form low order nonlinear models which include the entire range of dynamics of an inlet, ramjet, or scramjet, has not yet been accomplished. First, the model must be capable of transitioning from one type of behavior to another, and allowing both behaviors to simultaneously coexist. For example, the shock in a supersonic inlet can be in a started mode, which corresponds to a point attractor for the state space system, or it can be in buzz mode, which corresponds to a limit cycle for the state space system. Usually both behaviors are possible simultaneously; the mode being dependent upon the initial conditions

and the magnitude of any perturbations. The preservation of multiple operating conditions/attractors and the maintenance of their dimension is addressed further in [Mossayebi, Hartley, & DeAbreu-Garcia; and Hartley, Killory, DeAbreu-Garcia, Abu Khamseh].

Four techniques are suggested for future consideration. One, the method of [Martin] allows transitioning through preprogrammed logic. When a transition is called for, a new model is inserted for the old one. Although crude, the method certainly works. Second, numerical optimization of a low order nonlinear model from very accurate CFD models of all necessary phenomena is considered. Here, it would be necessary to have a two or three space dimensional model to generate the data, as most instabilities fundamentally require two or more space dimensions to represent them. Also, it would be necessary to choose an appropriate model structure which would not be readily apparent initially. This is probably an approach where neural networks could work quite well due to the large amount of uncertainty. Third, a model reduction technique that appears to be applicable to nonlinear systems is aggregation [Aoki]. This method essentially allows the user to choose the combination of any desired states to keep for the reduced order model. It is then possible to algebraically eliminate the remaining combination of states. This research is currently being pursued. Fourth, spectral methods for the Euler equations have a tremendous potential for generating these accurate low order large perturbation models [McCaughan; Culick, Lin, Jahnke, & Sterling]. These methods assume an infinite orthogonal set of spatial eigenfunctions for the spatial boundary value problem. Using separation of variables and some cancellation, the temporal coefficients for the spatial eigenfunctions form a low order set of nonlinear ordinary differential equations for a subset of the spatial eigenfunctions. The resulting simulation then would yield a spatially continuous solution which would change as the temporal coefficients changed. The major drawback of this approach is that, as usual, hyperbolic systems like the Euler equations do not readily lend themselves to this approach. More information can be found in [Gottlieb & Orszag]. It should be noted that this approach has been very effective for other flow systems including turbulence [Berge, Pomeau, Vidal; McCaughan].

Section 5. Conclusions

A unified systematic modeling approach has been presented for the modeling of high speed propulsion systems. When choosing a particular modeling approach, the decision between phenomenological accuracy and applicable complexity must always be made. This is true for both control design and for control evaluation, or real-time simulation. The methods discussed here are for the quasi-one-dimensional Euler equations of gasdynamic flow. The basic methodology and organization applies, however, to any other nonlinear spatially distributed system. The essential nonlinear features accurately represented by the quasi-one-dimensional Euler equations and the modeling methods discussed here are large amplitude nonlinear waves, including moving normal shocks, hammer shocks, simple subsonic combustion via heat addition, temperature dependent gases, detonations, and thermal choking. For accurate representations of oblique shocks, inlet buzz, boundary layers, flow separation, turbulence, and combustion instabilities, it would be necessary to consider at least two space dimensions in the Euler equations and viscosity would need to be added. This is the next logical step in the development of modeling methods for the control of high speed propulsion systems.

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JOURNAL ARTICLES:

SUBMITTED (or soon to be)

"A Hierarchy for Modeling High Speed Propulsion Systems," T.T.Hartley, J.A. DeAbreu, K. Melcher, C. Lorenzo, to be submitted to AIAA Journal of Propulsion and Power, Spring 1992.

"Approximate Truncated Balanced Realizations for Reducing Infinite Dimensional Systems," T.T. Hartley, J.A. De Abreu-Garcia, to be submitted to The Journal of The Franklin Institute, January, 1992.

"Methods for Developing Linear Reduced Models for Internal Flow Propulsion Systems," A. Chicatelli & T.T. Hartley, submitted to AIAA Journal of Propulsion and Power, September 1990.

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"A Fundamental Theorem for the Model Reduction of Nonlinear Systems," F. Mossayebi, T.T. Hartley, J.A. De Abreu-Garcia, The Journal of the Franklin Institute, Vol. 329, No. 1, pp 145-153.

"On the Equivalence of Multidimensional Filter Stability and von Neumann Stability," T.T. Hartley, to appear in the IEEE Trans. Circuits and Systems, 1991.

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"Physical Lumping Methods for Developing Linear Reduced Models for High Speed Propulsion Systems," S. Immel, T.T. Hartley, & J.A. DeAbreu-Garcia, submitted to the IEEE Conference on Control Applications, January, 1992.

"An Input-Output Separation Principle for Observing and Controlling Spatially Distributed Systems, T.T. Hartley & Lei Xia, submitted to the IEEE Conference on Control Applications, January, 1992, (will follow later).

"Modeling of Linear Isentropic Flow Systems," A. Sarantopoulos & T.T. Hartley, Proc. IEEE International Conference on Systems Engineering, Dayton, August, 1991.

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"Three Dimensional Root Locus Representations for Distributed Parameter Systems," J. Hariharan & T.T. Hartley, in the Proceedings of the 20th Annual Pittsburgh Conference on Modeling and Simulation, April, 1989.

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Reviewed Reports:

"Exact and Approximate Solutions to the Oblique Shock Equations for Real-Time Simulation," T.T. Hartley, R. Brandis, & F. Mossayebi, NASA Contractors Report 187173, August 1991.

"Numerical Methods for Large Perturbation Real-Time Simulation of Transonic Flows," T.T. Hartley, K. Melcher, & W. Bruton, NASP Tech. Memorandum 1062, 1989.

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"A Simple Method for Simulating Gasdynamic Systems," T.T. Hartley, Internal Report, On file with T.T. Hartley (U. of Akron) or Kevin Melcher (NASA Lewis).

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Ph.D. DISSERTATIONS

In Progress

"Modeling of Internal Flow Propulsion Systems," A. Chicatelli, In Progress.

"Control of Distributed Parameter Systems," Lei Xia, In Progress.

"Modeling of Linear Wave Phenomena," A. Sarantopoulos, In Progress.

M.S. THESES

Completed

"Identification Methods for the Control of Propulsion Systems," Liane Piercy, completed December 1990.

"Modeling and Reduction of Internal Flow Propulsion Systems," Amy Chicatelli, completed May, 1990.

"Real-Time Simulation of Internal Flow Propulsion Systems using Matrix Stability Region Placement," (with S.R. Pansino, YSU), Faramarz Mossayebi, comp. May, 1990, Youngstown State University.

SENIOR HONOR STUDENTS DIRECTED

"Model Reduction of Infinite Dimensional Systems via Optimization," Behzad Dariush, 1990-1991.

"Model Reduction of a Thermal System," Kevin Kosisko, 1989-1990.

"Finite Difference Methods for the Control of Flexible Space Structures," Dennis Hardesty, 1988-89.