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Short Paper

FREQUENCY-DOMAIN MODELING OF NONLINEAR MULTIVARIABLE SYSTEMS*

A. NASSIRHARAND[1] AND J. H. TAYLOR[2]

Abstract. A frequency-domain technique for the input/output (I/O) characterization of stable, multivariable, and highly nonlinear systems (e.g., industrial robots, aerospace vehicles, chemical processes) is presented. This approach requires only that the nonlinear system is representable in state-variable differential equation form, and that it is possible to integrate the system of equations numerically when input signals are sinusoidal. This technique is not restricted with respect to system order, number or type of nonlinearities, or configuration.

This I/O characterization technique involves determining the in-phase and quadrature components of the nonlinear system response to sinusoidal inputs of various amplitudes over a specified set of frequencies. These sinusoidal-input describing function (SIDF) models are obtained by exciting all input channels at one time with sinusoids of different but nearly equal frequencies, integrating the dynamic equations of motion over time, and simultaneously performing a Fourier analysis (evaluating Fourier integrals of the output signals). Once the Fourier integrals have reached steady-state, they are used to define the SIDF I/O model. Repeating this procedure for various amplitudes of the input signal will result in a number of matrix SIDF I/O models; the use of such models as the basis for multivariable nonlinear control system synthesis is currently under investigation.

Key Words—Nonlinear control, robust control, frequency domain modeling, describing function methods, Fourier analysis, computer-aided system design, software tools.

1. Introduction

One major distinction between linear and nonlinear systems is the fact that the behavior of the latter is generally amplitude dependent while that of the former is not. Small-signal linearized models of nonlinear dynamic systems are the most tractable in terms of mathematical analysis and design techniques, but such models cannot characterize the amplitude sensitivity of the system, which may be an important feature. In fact, accounting for and accommodating nonlinear system amplitude sensitivity may be the primary factor in achieving or failing to achieve a robust control system design. Therefore, extending the rich analysis and design methodologies for linear systems to accommodate the amplitude dependence of nonlinear systems represents a major accomplishment. Describing function techniques have often been successful in fulfilling this objective (Atherton, 1975; Gelb and Vander Velde, 1968).

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This presentation is an extended and corrected version of Nassirharand and Taylor (1988).

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Representing a nonlinear system with a sinusoidal-input describing function (SIDF) model has proven to be a useful approach for the analysis and design of nonlinear control systems. One recent body of results in this area may be found in Taylor (1982; 1983), Taylor and Strobel (1984; 1985) and Nassirharand et al. (1988). The advantages of using SIDF input/output (I/O) models for nonlinear control system analysis and design have been discussed in detail elsewhere (e.g., in Taylor, 1982; 1983), namely:

i) The method is applicable to nonlinear systems of great generality, including those having discontinuous or multi-valued nonlinearities (e.g., relays, hysteresis, and backlash) or nonlinear functions of several variables, in any configuration. In fact, the approach presented here can be used to obtain SIDF models for any nonlinear system which is representable in standard state-variable differential equation form with no restriction on the nonlinearity type, system order, number of nonlinearities, or structure.
ii) The amplitude dependence of the nonlinear plant is retained, giving the designer a realistic basis for robust control system design.

SIDF I/O models have important applications in two areas: the "diagnosis" of nonlinear plants (the amplitude sensitivity of the SIDF model is a good measure of how nonlinear the plant is in the operating regimes under consideration and thus serves as an indicator of the difficulty of achieving a robust control system design) and as a basis for nonlinear control system synthesis. Therefore, extension of SIDF-based modeling and synthesis techniques to the multi-input/multi-output (MIMO) case is a substantial contribution. This presentation treats MIMO SIDF modeling; first strides in the synthesis of nonlinear MIMO control systems are dealt with in Nassirharand and Taylor (1990). The specific focus of this presentation is the full extension of the SIDF I/O modeling approach of Taylor (1983; 1985) to the case of MIMO systems.

2. SIDF Modeling

One approach to using SIDFs to characterize the input/output behavior of a nonlinear plant involves replacing each nonlinear term in the mathematical model with a quasilinear gain function which depends on the amplitude of the nonlinearity input signal (see Atherton, 1975 or Gelb and Vander Velde, 1968). The quasilinear gain function is referred to as the *describing function* for that nonlinearity, and it is based on the assumed form of the input signal, here taken to be sinusoidal. The quasilinear system equations are used to formulate the harmonic balance relations which can then be solved to obtain the SIDF I/O model. This methodology is outlined completely in Taylor and Strobel (1984).

The choice of an assumed form for each nonlinearity input signal has been the subject of much debate. It has been argued that selection of different forms of the input signal leads to contradictory information regarding the behavior of the system. In Taylor (1983), the describing function for the saturation nonlinearity was presented for a number of assumed input distributions. As shown in Fig. 1, it was observed that the describing function gain versus input amplitude characteristic for a variety of distributions (gaussian, triangular, uniform, sinusoidal, and bimodal triangular) is not very sensitive: The gains for a limiter with these input distributions are within 10 to 15 percent of the gain plot for uniformly distributed inputs, which is usually comparable in accuracy to a

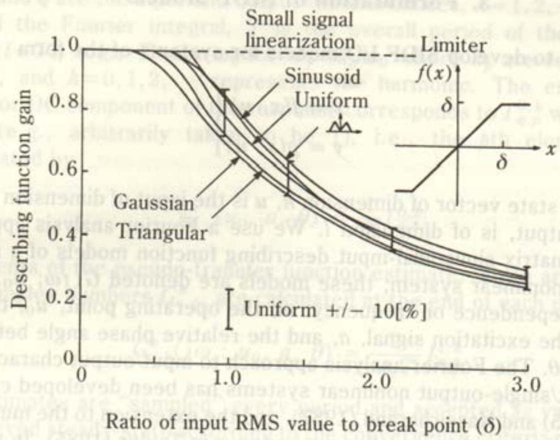

Fig. 1. DF gain sensitivity to amplitude distribution.

designer's knowledge of most model parameters. Several other nonlinearities (sine(x) and x^3) were investigated, with similar results.

A second approach to determining SIDF I/O models for nonlinear systems *completely avoids this argument about the form of nonlinearity input signals* (see Taylor and Strobel, 1984; Taylor, 1985). This involves developing a nonlinear simulation of the system, executing simulations with sinusoidal input excitation of various amplitudes of interest, and performing Fourier analysis of the steady-state system output response to obtain the corresponding I/O characterization in terms of magnitude and phase. Clearly, there is no underlying assumption that the input to each nonlinearity is approximately sinusoidal in form.

In this work, we aim at advancing systematic controller design techniques for highly nonlinear systems, especially for cases where the existing elegant mathematical theories are not applicable, by completing the extension of SIDF I/O modeling techniques to the multivariable case. We have concentrated on the I/O characterization of systems which are of interest in industrial settings (e.g., robotics) and aerospace applications (e.g., flight control). Such systems are typically excited by command signals whose amplitude distributions resemble the sinusoidal case, in the sense that there are usually definite limits (minimum and maximum input values) and the input is more often near these limits than "near the middle". For this purpose, we choose to obtain the sinusoidal-input describing function models of nonlinear systems covering the range of input amplitudes that will be encountered; this will provide a basis for *robust* design (Taylor, 1982), since sensitivity of the plant behavior to input amplitude is one of the most important issues in robustness and SIDF I/O models are the least conservative type of model that accurately accounts for this factor. Hence, one does not unnecessarily sacrifice system performance to achieve a robust design.

3. Formulation of SIDF Models

The goal is to develop SIDF I/O models for systems of the form

$$\left.\begin{aligned}\dot{x} &= f(x, u)\\ y &= g(x, u)\end{aligned}\right\}, \tag{1}$$

where x is the state vector of dimension n, u is the input of dimension m, and y, the system output, is of dimension l. We use a Fourier analysis approach to compute the matrix sinusoidal-input describing function models of a multivariable (MIMO) nonlinear system; these models are denoted $\boldsymbol{G}(j\omega;\, u_0,\, a,\, \theta)$ to signify their dependence on frequency, ω, the operating point, u_0, the vector amplitude of the excitation signal, a, and the relative phase angle between the input signals, θ. The Fourier analysis approach to input/output characterization of single-input/single-output nonlinear systems has been developed completely in Taylor (1985) and Nassirharand (1987), and the extension to the multivariable case has been indicated in a preliminary manner in Taylor (1985). In this work, the Fourier analysis characterization technique for the multivariable case is fully extended.

Before proceeding, the following key points should be noted:

- The matrix I/O transfer relation of a multivariable nonlinear system cannot be obtained by simultaneously exciting all inputs with the same frequency, because it would then be impossible to determine the separate effects of each input on each output.
- SIDF I/O models of multivariable nonlinear systems cannot be obtained by exciting individual inputs one-at-a-time, because the principle of superposition is not valid.

Therefore, in order to obtain matrix SIDF models, it is necessary to excite all input channels simultaneously with different but nearly equal frequencies.

3.1 Simulation and Fourier analysis The nonlinear system modeled by Eq. (1) is simulated for input signals defined by

$$u_p(t) = u_{0,p} + a_p\cos(\omega_p t+\theta_p), \quad p = 1, 2, \cdots, m, \tag{2}$$

where $u_{0,p}$ is the "DC component" of the input signal or operating point, a_p is the amplitude of the pth excitation signal, ω_p and θ_p are the frequency and relative phase of the pth sinusoidal input, and p is the input channel index. Note, from the nature of the Fourier analysis performed below, that the various input frequencies must be related rationally, e.g., $\omega_1/\omega_2=3/4$ for the two-input case. Observe also that the frequency ratio (and the relative phases of the input sinusoids) may be critical if the integers are small, due to possible cross-modulation effects. For larger integers, e.g., $\omega_1/\omega_2=11/13$, cross-modulation will generally be negligible—although this should be verified in any event.

The dynamic equations of motion are numerically integrated to obtain the outputs as a function of time, $y_q(t)$, $q=1,2,\cdots,l$. The matrix Fourier integrals for period k, denoted $I_{q,p}^{h,k}$, are integrated simultaneously,

$$I_{q,p}^{h,k} = \int_{(k-1)T}^{kT} y_q(t)\exp(-jh(\omega_p t+\theta_p))\,dt, \tag{3}$$

where p and q are the input and output channel indices, $k=1,2,\cdots$ denotes the period of the Fourier integral, T is the overall period of the input vector $(u(t)=u(t+T)$, e.g., $T=2\pi/\omega_0$ for $\omega_p=k_p\omega_0$ where k_p are relatively prime integers), and $h=0,1,2,\cdots$ represents the harmonic. The estimate of the constant or DC component of the response corresponds to $I_{q,p}^{0,k}$ where p may be ignored (e.g., arbitrarily taken to be 1), i.e., the pth element of y_0 is approximated by

$$y_{0,q}^k(u_0,\ a,\ \theta) = \frac{1}{T} I_{q,1}^{0,k}, \tag{4}$$

and elements of the pseudo-transfer function estimate, which are represented by the complex numbers $G_{q,p}^k$, are calculated at the end of each period T to be

$$G_{q,p}^k(j\omega_q;\ u_0,\ a,\ \theta) = \frac{2}{a_p T} I_{q,p}^{1,k}. \tag{5}$$

These estimates are "sampled" every period and accepted as valid when they have achieved steady-state according to the convergence criteria defined below; in vector/matrix notation, the converged quantities in Eqs. (4), (5) are elements of y_0 and $G(j\omega;\ u_0,\ a,\ \theta)$ respectively. In order to analyze the importance of the higher harmonic effects, one may also evaluate

$$G_{q,p}^{h,k}(j\omega_q;\ u_0,\ a,\ \theta) = \frac{2}{a_p T} I_{q,p}^{h,k}, \quad h = 2,\ 3,\ \cdots, \tag{6}$$

if $G_{q,p}^{h,k}$ for $h>1$ is substantially less than $G_{q,p}^k$, then the hth harmonic content can be said to be small in comparison with the fundamental.

In summary, for a given input amplitude vector, a, and relative phase vector, θ, Eq. (5) is evaluated over a set of frequencies covering the range of interest to obtain the quasilinear model of the nonlinear plant. This procedure is repeated for various input amplitudes to obtain a number of quasilinear models of the nonlinear plant. The outcome of such a study is illustrated in Sec. 5 (see Figs. 3–10).

3.2 Convergence testing Two error control parameters are associated with the magnitude and phase of $G(j\omega;\ u_0,\ a,\ \theta)$. The Fourier integrals are said to have converged if the following conditions are satisfied:

$$\left.\begin{aligned} |M_{q,p}^k - M_{q,p}^{k-1}| &< \varepsilon_M \\ |\phi_{q,p}^k - \phi_{q,p}^{k-1}| &< \varepsilon_\phi \end{aligned}\right\}, \tag{7}$$

where $M_{q,p}^k$ and $\phi_{q,p}^k$ represent the *log magnitude* and *phase* associated with the element $G_{q,p}^k(j\omega;\ u_0,\ a,\ \theta)$. Log magnitude and phase are effectively dimensionless quantities (e.g., decibels and degrees), so absolute error is tested rather than relative error. Furthermore, polar coordinates are used rather than cartesian ($M_{q,p}^k$ and $\phi_{q,p}^k$ rather than the real and imaginary parts of $G_{q,p}^k$) because this simplifies error testing at points near real- and imaginary-axis crossings. Finally, the user should inspect the output signals corresponding to at least some of the data points, to ensure that they are *periodic* and that they are not *excessively small* in value; otherwise the Fourier analysis results may be inaccurate or misleading. This is especially important for high frequencies where attenuation may be high and for very small and large input amplitudes where nonlinear effects such as discontinuous switching and saturation may be severe. A software package for SIDF I/O modeling should provide this capability in a flexible interactive environment to facilitate such engineering judgements.

4. Software

A computer-aided engineering environment has been developed to automate the generation of the matrix SIDF models for the class of nonlinear systems considered in this study. The user must supply a subroutine containing the dynamic model of the nonlinear plant under study in the state-variable form indicated in Eq. (1); any number of plants may be defined and linked to the package. The software is command driven; a brief description of the software command set is as follows:

PLANT,*n*: specifies the particular (*n*th) plant whose SIDF I/O model is to be generated.

FREQ: specifies the frequency set which is to be used to evaluate $\boldsymbol{G}$. This command may be used to generate *nw* frequencies using either logarithmic or linear spacing, to define the frequency list directly from the command line, or to read the set from an input file; these selections are specified by the command-line options *LOG*, *LIN*, *MAN*, or *<fname1*, respectively, where *fname1* is a file specification. A *-ADD* option allows the user to add a new set of frequencies to the existing set, and the *>fname2* option may be used to store the existing frequency set onto a data file for later use.

AMPL: specifies the amplitude vector and operating point characterizing the input signal (Eq. (2)); these parameters may be input on the command line or read from a file.

ERR: specifies the convergence error control parameters (Eq. (7)); another parameter *ncyc* associated with this command may be used to limit the number of integration cycles (to stop integration after $k = ncyc$ periods in Eq. (3)).

DISPL: specifies, via the appropriate option, the display of various parameters: $A \rightarrow$ the input signal parameters; $F \rightarrow$ the set of input frequencies; $E \rightarrow$ the error control parameters; and $R \rightarrow$ the nonlinear system frequency-response ($R \rightarrow \boldsymbol{G}$).

INT: specifies the integration method: *dt*, *eps*, *hmin*, *dxsav* correspond to integration step-size, convergence tolerance used by the variable step-size Runge-Kutta routine, the minimum value of the step-size, and the tolerance for saving the output signals for plotting, respectively; the option *FIX* may be specified to enable the fixed step-size Runge-Kutta integration routine.

FRESP,*n*,: generates the SIDF model; the parameter *n* allows the user to view the system output responses every *n*th cycle.

PLOT: plot $\boldsymbol{G}$ in either Bode or Nyquist form.

MENU: display the command set upon the execution of each command; to suppress the menu display, the **MENU OFF** command may be executed.

QUIT: quit the session.

Note that the present software does not allow user-defined frequency ratios. Appropriate extensions are planned to allow this ratio to be set arbitrarily.

5. Demonstration Problem

Consider the nonlinear system defined by the block diagram shown in Fig. 2. It is desired to characterize the input/output behavior of the system for input amplitudes of 0.5, 1.0, 2.0, 4.0 and 8.0 about the operating point $u_0=0$ over the range of frequencies $0.1 \le \omega \le 30$ [rad/sec]. The mathematical description of the system is:

$$\left.\begin{aligned} \dot{x}_1 &= x_2 + T_1(u_1) \\ \dot{x}_2 &= -x_1^3 - 2.0x_2 + T_2(u_2) \end{aligned}\right\} \quad (8)$$

where

$$\left.\begin{aligned} T_1 &= \begin{cases} m_1 u_1 & \text{if } |u_1| \le \delta_1 \\ \mathrm{Sign}(u_1)\cdot(m_1\delta_1 + m_2(|u_1| - \delta_1)) & \text{if } |u_1| > \delta_1 \end{cases} \\ T_2 &= \begin{cases} m_2' u_2 & \text{if } |u_2| \le \delta_2 \\ \mathrm{Sign}(u_2)\cdot(m_1'\delta_2 + m_2'(|u_2| - \delta_2)) & \text{if } |u_2| > \delta_2 \end{cases} \end{aligned}\right\} \quad (9)$$

A computer model of the system is developed and linked to the software package outlined above. The specific nonlinearity parameter values were taken to be: $\delta_1=\delta_2=1.0$, $m_1=m_1'=1.0$, and $m_2=m_2'=0.5$. We then proceed as follows:

1. Specify the plant identification number (5), the first amplitude of the excitation signal (both input amplitudes 0.5 about the operating point $u_0=0$), the error control parameters, the frequency set, and the integration parameters:

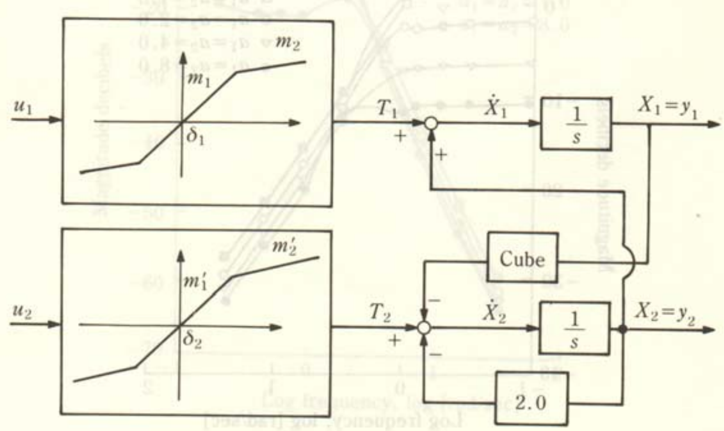

Fig. 2. Schematic of Sec. 5 sample problem.

PLANT,5,
AMPL,2,0.5,0.5,0.,0.,
ERR,0.1,1.0,20,0.0,0.0,
FREQ,MAN,0.1,0.3,0.5,0.8,1.,3.,5.,8.,10.,30.,
INT,0.01,FIX,

2. Execute the **FRESP,15**, command to generate the SIDF models; this will display the outputs every 15th cycle.
3. Display G, either via the **DISPL,R** command (for a table of frequencies, real and imaginary part of G, and error magnitude and phase), or frequency response plots may be examined via the **PLOT** command.
4. Four more cycles of the **AMPL** command followed by **FRESP** are used to generate the SIDF models at the remaining amplitudes (1.0, 2.0, 4.0, 8.0) of the input signals; the results may be overlaid using the *OV* option of the **PLOT** command (see Figs. 3–10).

Figures 3 through 10 demonstrate that the system under study behaves very differently for different input amplitudes, especially at low excitation frequencies, and thus should be considered to be quite highly nonlinear. The design of a linear controller for this plant would be a difficult task, and failure to accommodate the amplitude sensitivity in some way would be likely to cause problems relative to robustness. A linear controller synthesis approach that does account for this behavior is presented in Nassirharand and Taylor (1990). Nonlinear control synthesis methods may be indicated, to obtain a control system that is more robust (less sensitive to input amplitude compared with a feedback system with linear control).

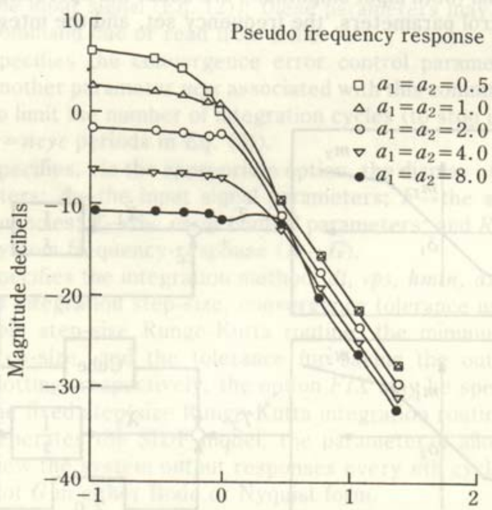

Fig. 3. Pseudo bode magnitude plot of $G^k_{1,1}$.

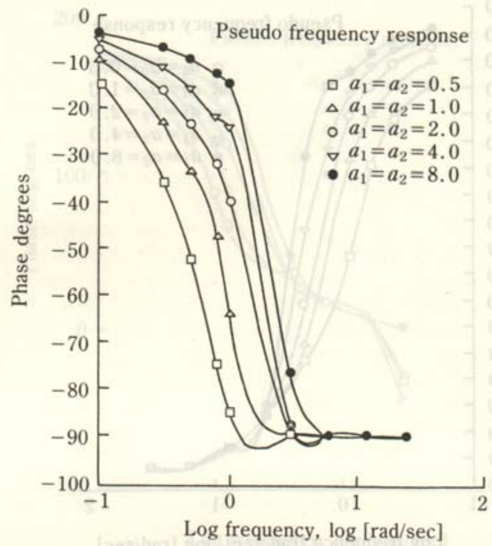

Fig. 4. Pseudo bode phase plot of $G^k_{1,1}$.

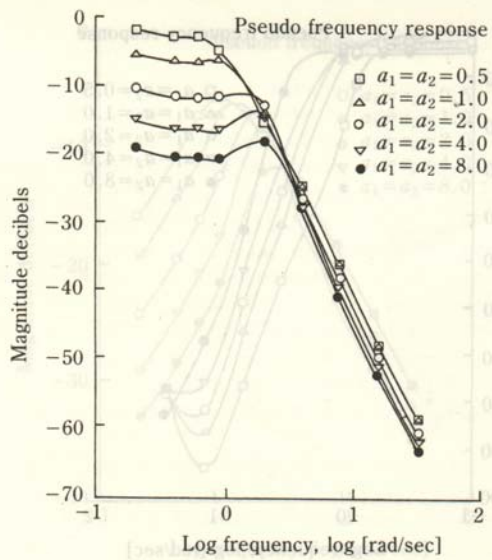

Fig. 5. Pseudo bode magnitude plot of $G^k_{1,2}$.

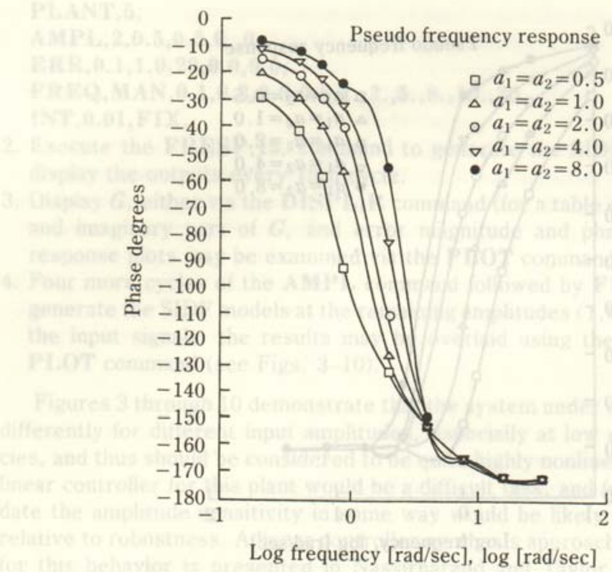

Fig. 6. Pseudo bode phase plot of $G^k_{1,2}$.

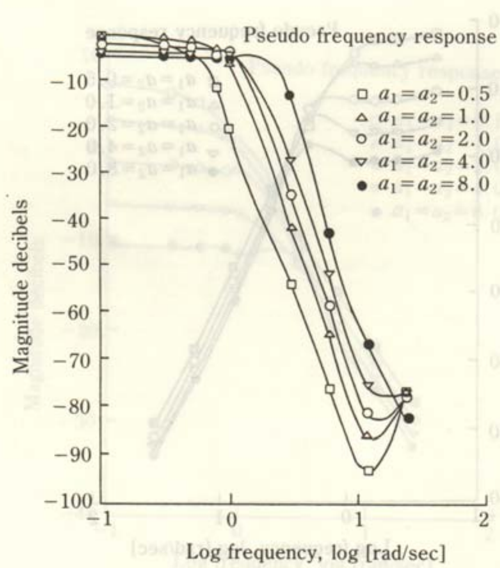

Fig. 7. Pseudo bode magnitude plot of $G^k_{2,1}$.

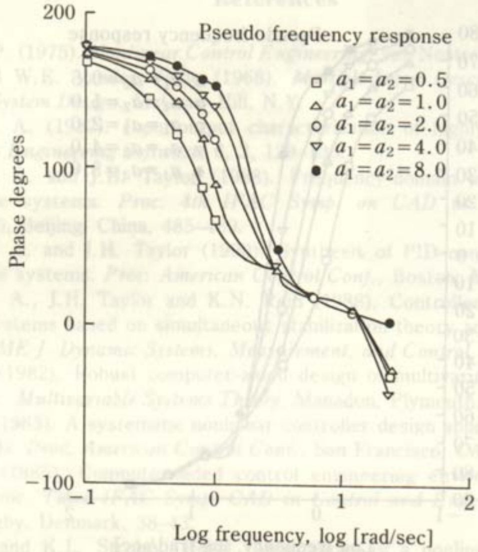

Fig. 8. Pseudo bode phase plot of $G^{*}_{2,1}$.

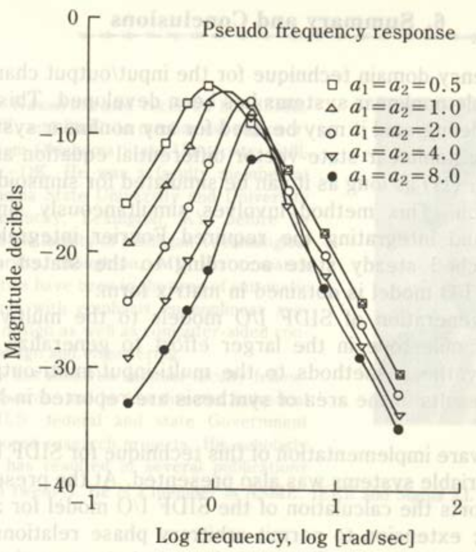

Fig. 9. Pseudo bode magnitude plot of $G^{*}_{2,2}$.

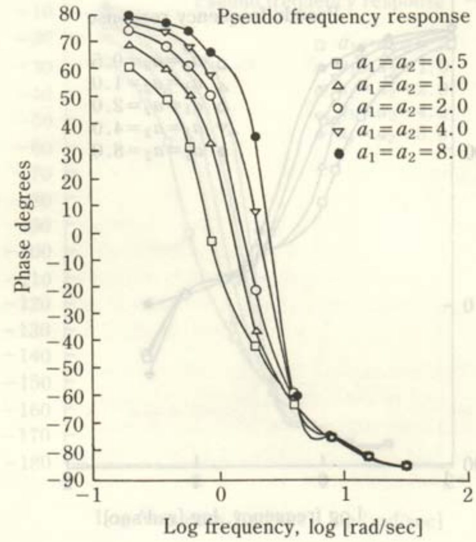

Fig. 10. Pseudo bode phase plot of $G^k_{2,2}$.

6. Summary and Conclusions

A general frequency-domain technique for the input/output characterization of stable multivariable nonlinear systems has been developed. This approach is called SIDF I/O modeling, and it may be used for any nonlinear system that can be represented by a nonlinear state-vector differential equation and nonlinear output equation (Eq. (1)) as long as it can be simulated for sinusoidal inputs via numerical integration. This method involves simultaneously simulating the nonlinear system and integrating the required Fourier integrals; once the solutions have reached steady state according to the stated convergence criterion, the SIDF I/O model is obtained in matrix form.

Extending the generation of SIDF I/O models to the multivariable case represents a major milestone in the larger effort to generalize SIDF-based nonlinear control synthesis methods to the multi-input/multi-output (MIMO) case. Preliminary results in the area of synthesis are reported in Nassirharand and Taylor (1990).

A versatile software implementation of this technique for SIDF I/O modeling of nonlinear multivariable systems was also presented. At the present time, the software only supports the calculation of the SIDF I/O model for zero relative input phase ($\theta=0$); extension to permit arbitrary phase relations among the input signals is straightforward. The technique and the associated software package promise to be useful for extending the existing frequency-domain controller synthesis techniques for single-input/single-output systems to the multivariable case.

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From 1969 to 1972, Dr. Taylor was a visiting Assistant Professor at the Indian Institute of Science, Bangalore, India, where he taught control theory and nonlinear systems analysis. In 1973, he joined The Analytic Sciences Corporation (TASC), Reading, MA, where he developed analysis techniques for nonlinear systems. During 1978–1981, Dr. Taylor was an Associate Professor of Mechanical and Aerospace Engineering at Oklahoma State University, Stillwater, OK. He taught systems and controls courses, and continued research in nonlinear systems.

Dr. Taylor joined GE Corporate Research and Development in July, 1981. Research areas include nonlinear systems analysis and design, computer-aided control engineering (CACE), and expert systems for control (both for CACE and real-time control). He is Project Leader for parallel Air Force and GE sponsored programs to develop software environments for CACE. He also leads the Intelligent Processing of Materials controls effort.

Dr. Taylor is a member of IEEE, ASME, AAAI, TBΠ and ΣΞ. He holds adjunct faculty positions at RPI and Oklahoma State University, and has numerous publications in nonlinear systems theory and CAD for control (contributions to five books and about four dozen papers). He also organized and was primary lecturer in five short courses in nonlinear controls at Union College and MIT. GE has granted Dr. Taylor several awards for project leadership and publications.