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APPLICATION OF PRONY ANALYSIS TO THE DETERMINATION OF MODAL CONTENT AND EQUIVALENT MODELS FOR MEASURED POWER SYSTEM RESPONSE

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ABSTRACT

Prony analysis is an emerging methodology that extends Fourier analysis by directly estimating the frequency, damping, strength, and relative phase of the modal components present in a recorded signal. This paper extends earlier work that concentrated upon power system planning applications, for stability program outputs. Results are presented here for modal analysis and detailed model construction based upon response data obtained through large-scale tests of the western U.S. power system. BPA's optimal modeling program, SYSFIT, is used to supplement the measurements.

KEYWORDS: Prony, signal analysis, modeling, identification, dynamics, eigenvalue, singular value.

I. INTRODUCTION

Prony analysis [1,3-6] is an emerging method that fits a linear parametric model to a measured signal y(t). The model is in the form of poles and residues that, collectively, constitute a modal decomposition of the signal. If y(t) is the output of a linear dynamic system, then, under suitable conditions, the signal modes will be those of the system itself. There are many uses for such a tool in the analysis, modeling, and control of power system dynamics. System planning applications, based upon stability program outputs, are illustrated in [1]. This paper focuses upon its application to response data obtained through large-scale field tests, with supplemental use of Fourier analysis and frequency domain fitting of structured dynamic models [2].

Insight into the signal environment is critical to the effective development and use of signal analysis tools, especially those tools which attempt model identification. Information concerning the signal environment for ambient measurements and low-level tests on the western U.S. power system can be found in [7-9]. A detailed examination of this issue for high-level tests is presented in Section IV.

Any identification procedure is essentially a curve fitting algorithm, augmented by accessory constraints designed to make the results physically meaningful. The constraints may encapsulate a great deal of physical law, engineering insight, and mathematical sophistication. Despite this, the identified model will usually contain features that are merely part of the curve fitting process. Sometimes this is a small price for obtaining a low order approximation to a high order process. In other situations it is necessary either to distinguish those features that are physically meaningful from those which are not, or to maximize model realism in some sense.

A realistic model constructed from measured system response should

- have no more structure than is needed to explain the observed phenomena. (This is the "parsimony principle".)
- be consistent with the parent signal in the frequency domain.
- not show major changes for reasonable changes in the way the parent signal is processed.
- be consistent with models obtained from related signals.

The development to follow will proceed in this context.

II. MATHEMATICAL PRELIMINARIES

Let a linear time-invariant (LTI) dynamic system be brought to an initial state $x(t_0)=x_0$ at time $t_0=0$, by some test input or disturbance. Then, if the input is removed at $t=t_0$ and there are no further inputs or disturbances to the system, it will respond according to a differential equation of form

$$\dot{x} = A x \tag{1}$$

Let λ_i, p_i, q_i^T be respectively the eigenvalues, right eigenvectors, and left eigenvectors [10] of the (n x n) matrix A. Then the modal transformation $x=[p_i]x_m$ produces

$$\dot{x}_m = [q_i^T]\ A\ [p_i]\ x_m = \Lambda\ x_m \tag{2}$$

where $\Lambda=\text{diag}(\lambda_i)$. Each component x_{im} of the modal state vector satisfies

$$x_{im} = x_{im,0} \exp(\lambda_i t) = (q_i^T x_0) \exp(\lambda_i t) \tag{3}$$

$$\text{and} \quad x(t) = \sum_{i=1}^{n} p_i\ (q_i^T x_0) \exp(\lambda_i t) \tag{4A}$$

$$= \sum_{i=1}^{n} R_i x_0 \exp(\lambda_i t) \tag{4B}$$

where R_i is an (n x n) residue matrix. Though x_0 (together with q_i^T) determines the stimulus to the mode associated with λ_i, the distribution of modal response among the components of x is entirely determined by the corresponding (n x 1) right eigenvector p_i. Thus information about p_i can be obtained by appropriate modal decompositions of x(t).

Suppose that there is just one output, of form

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$$y(t) = C\,x(t) + D\,u(t) \quad (5A)$$

where u(t) is the system input. Since u(t) is assumed zero,

$$y(t) = C\,x(t) \quad (5B)$$

$$= \sum_{i=1}^{n} B_i \exp(\lambda_i t) \quad (5C)$$

$$= \sum_{i=1}^{Q} A_i \exp(\sigma_i t) \cos(2\pi f_i t + \Phi_i) \quad (5D)$$

The B_i are termed signal residues. Prony methods and their recent extensions directly estimate the parameters in (5C) and (5D) from an observed record for y(t). In doing this it may also be necessary to model offsets, trends, noise, and other extraneous effects in the signal.

Let the record for y(t) consist of N samples $y(t_k)=y(k)$, k=0,1,...,N-1 evenly spaced by an amount Δt. The strategy for obtaining a Prony solution (PRS) can be summarized as follows:

STEP 1. Fit the record with a discrete linear prediction model (LPM) of form

$$y(P+k) = a_1 y(P+k-1) + \ldots + a_P y(k) \quad (6)$$

STEP 2. Find the roots of the characteristic polynomial associated with the LPM of Step 1.

STEP 3. Using the roots of Step 2 and the complex modal frequencies λ_i of the signal, determine the amplitude and initial phase for each mode.

These steps are performed in z-domain, following one or another of several procedures that refine the basic method described in [4]. This produces

$$\hat{y}(k) = \sum_{i=1}^{P} B_i z_i^k, \quad (7A)$$

$$z_i = \exp(\lambda_i \Delta t). \quad (7B)$$

The reconstructed signal $\hat{y}(k)$ will usually fit y(k) inexactly. An appropriate measure for the quality of this fit, used here, is the signal-to-noise ratio

$$SNR = -20 \log \|\hat{y}(k)-y(k)\|/\|y(k)\| \quad (8)$$

where $\|\bullet\|$ denotes the usual root-mean-square norm and the SNR is in decibels (db).

III. IMPLEMENTATION

Prony analysis, introduced some 200 years ago [3], is just now becoming a tool for practical use. The underlying mathematics are outwardly straightforward, but numerically ill-conditioned. They demand very good algorithms, and modern computers. BPA's SIGPAKZ program makes extensive use of singular-value logic [10], and employs quadruple precision (REAL*16) arithmetic for the polynomial rooting at Step 2. It also incorporates recent advances in fast algorithms [11,12].

Power system applications pose some difficulties of their own. These include

- A true system dimension n that is infeasibly large for any fitted model.
- Effective signal dimensions that, while smaller than n, are large and unknown.
- Time-varying and/or nonlinear dynamics.
- Noise components in y(t).
- Hidden inputs to the system.

Signals tend to be "of full rank", in that a close fit requires a model order P approaching the upper limit N/2 [1]. The ability to construct high order models is a valuable asset, especially under severe noise conditions. SIGPAKZ was developed for this, and is commonly used to produce models of order 120.

IV. THE SIGNAL ENVIRONMENT FOR LARGE-SCALE TESTS

BPA regularly examines the dynamics of the western North American power system through measurements and direct tests [7-9]. In recent years the preferred test input has been a standard 1400 MW, 0.5 second load pulse from the Chief Joseph dynamic brake. This automatically triggers record collection by the Power System Disturbance Monitor (PSDM) at BPA's Dittmer Control Center. In the more recent tests data has also been recorded by other utilities, some of which are developing their own monitor systems. Coordination of these efforts is provided through the 0.7 Hz Oscillation Ad Hoc Work Group of the Western Systems Coordinating Council (WSCC).

The PSDM record shown in Figure 1 is typical. The quantity displayed there is power export to Pacific Gas and Electric (PG&E), on the Malin-Round Mountain 500-kV circuits of the Pacific AC Intertie. It is a good index signal for overall system dynamics. Its complexity, noise characteristics, and location can be detrimental to close identification of specific critical modes, however.

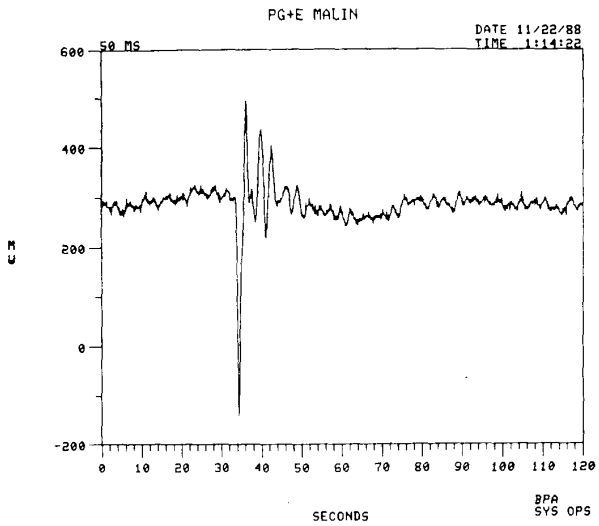

Figure 1. Ringdown of PG&E interchange power for brake pulse #1, 11/22/88

The brake energization of Figure 1 was performed at 0114:56 hrs. on November 22, 1988, with action of BPA's automatic generation control (AGC) system suspended. (The time is that for the monitor record, not the actual brake energization.) A second energization was performed 2 minutes later, with AGC active. The time of testing was selected to minimize interference from other system activity. Even so, the record suggests a persistent low frequency swing due to some earlier disturbance or input. This will appear as a "trend" during the processing of short record segments.

A useful indicator of the dominant modes in such a ringdown signal can be obtained through Fourier analysis. Usual BPA practice for PSDM records (which have a sample spacing Δt=0.05 second) is to process a 25.6 second segment starting about 0.1 second before the brake pulse. The segment is preprocessed by removing its initial offset, doubling its length through leftward zero fill, and multiplying it by a bell-shaped "Hanning" window [13], as in Figure 2. BPA's Fast Fourier Transform (FFT) program, SIGPAK, then produces a complex autospectrum A22 which, when divided point-by-point by the autospectrum all of the input pulse, gives a tabulated estimate for the complex transfer function T12.

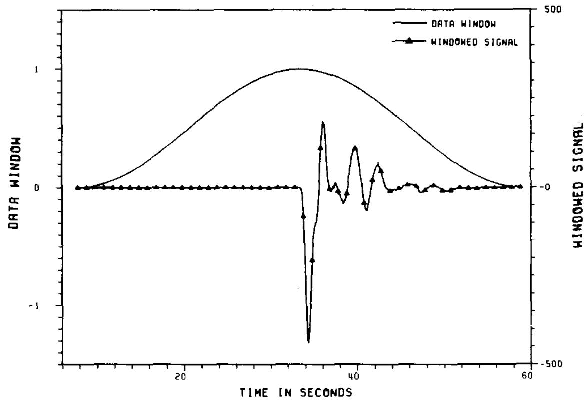

Figure 2. Ringdown signal prepared for Fourier analysis

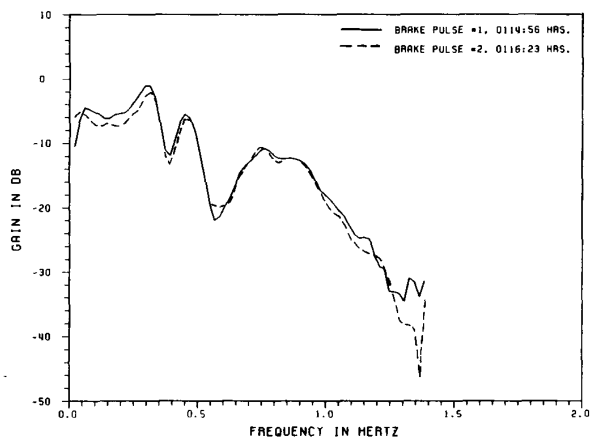

Figure 3A. PG&E T12 gain for tests of 11/22/88

Figures 3A and 3B show very repeatable T12 results for the two brake energizations of November 11. The gain differences at the lowest frequencies are probably due to trends. Similar tests were performed on April 10 and May 16 of 1989, but with a 15 minute spacing of the brake pulses. Figures 4,5 show good repeatability in both cases. April 18 results suggest some system change between energizations or some extraneous input to the system, "hidden" in the sense of not being apparent to the test instrumentation. Such uncertainty is a governing reality in the large-scale testing of power system dynamics.

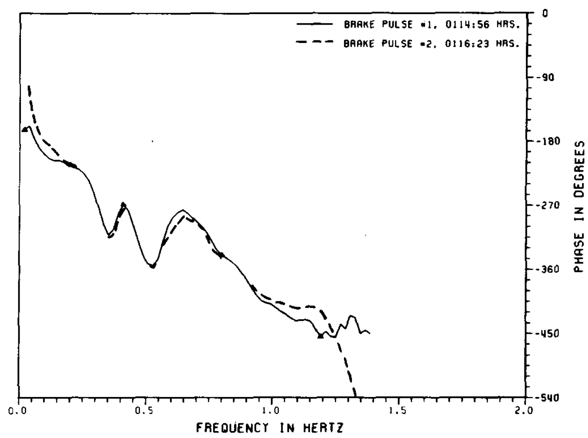

Figure 3B. PG&E T12 phase for tests of 11/22/88

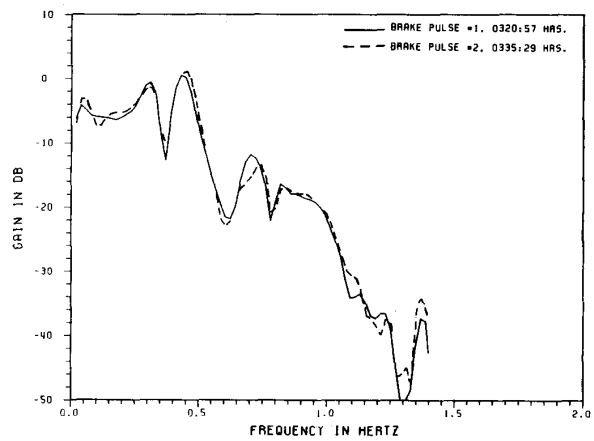

Figure 4. PG&E T12 gain for tests of 04/18/89

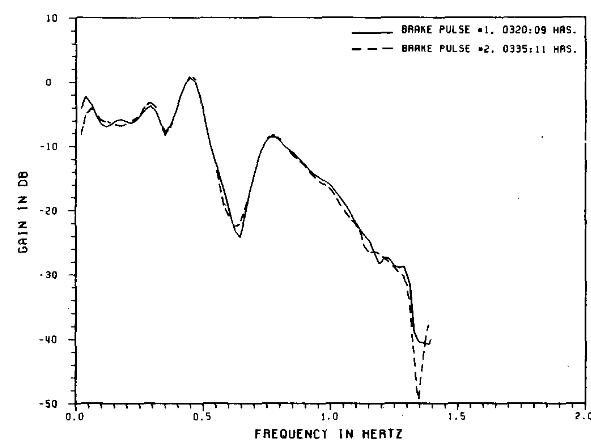

Figure 5. PG&E T12 gain for tests of 05/16/89

Equally important is the strong and highly structured ambient noise exemplified in Figure 1. Ambient measurements often seek information directly from this noise, denoted here as $\nu_s(t)$. Figure 6 shows a measured autospectrum for ν_s determined for a 2 minute period just before the first brake energization of April 18. While this record is too short to establish long-term behavior, comparison of Figures 4 and 6 demonstrates that the peaks in the noise spectrum are aligned with those in the system frequency response T12. Rather than being "white", ν_s has the same "coloration" as T12. It is useful to treat ν_s as an output produced by random load switching [8], represented as an equivalent noise input ν.

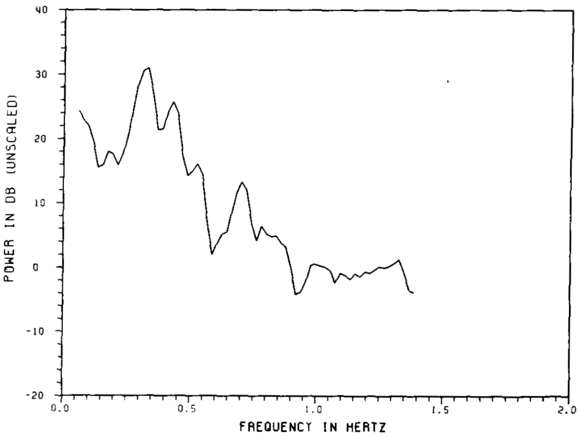

Figure 6. Noise spectrum before brake pulse #1, 04/18/89

Low-level tests mitigate ambient noise effects by averaging processes applied to long records. High-level tests do not afford this option, but must instead rely upon a high signal level, and upon processing methods that exploit the assumedly non-periodic nature of ν_s. The *short-term* characteristics of ν_s are not yet fully understood. This topic is revisited at various points in the sections to follow.

V. INITIAL RESULTS FOR THE TEST OF APRIL 18, 1989

This section provides initial results obtained for the western system test of April 18, 1989. Later reports will be more comprehensive, and will benefit from ongoing refinements to SIGPAKZ and the methods for applying it.

Figure 7 shows a Prony fit to a 51.2 second section of the PG&E ringdown for brake pulse #1. The SNR value, 32.79 db, is indicative of a good curve fit to this type of signal (high noise level, minimal offset). The extent to which the PRS represents actual system parameters must be judged by its consistency with results obtained for related signals, for reasonable changes in the processing controls, and by alternate methods.

Table I displays PRS results produced by sliding the processing window of Figure 7 along the signal in steps of 0.2 second, for a total of 4 solutions. Record length TBAR, indicated in the table header, was set to 25.6 seconds for consistency with FFT processing. LPOCON and PIRCON are assigned initial values for the linear prediction order n in (6) and a rank limit for a pseudo-inverse matrix used in Step 3

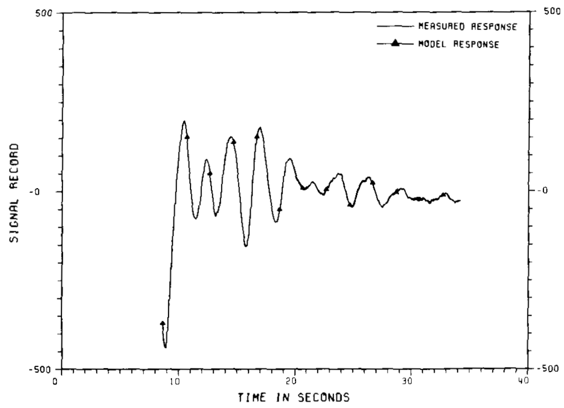

Figure 7. Prony fit for PG&E ringdown #1, 04/18/89

** CASE DM0418898.SGZ;52 [PG&E-MALIN MW] [4 WINDOWS][TSHIFT=0.2]
[BRAKE ON @ 07.85 SEC]
[TBAR=25.6 SEC] [MTREND=2]
[LPOCON,PIRCON=114,110]
[FTRIMH,FTRIML = 2.0,0.0]
DISPLAY TRIM LEVEL= 0.50000E-01

**PRONY S-TABLE FOR PRS NUMBER 1: TSPAN = [8.65, 34.15]
*SIGNAL-TO-NOISE RATIO = 32.7920 FOR NMODES = 58

MODE	DAMPING	FRQ (HZ)	REL WT	PHASE	AMPLITUDE	%DAMPING
1	0.0527669	0.0000000	0.210	0.00	57.35461	1.000
2	0.0030809	0.0336096	0.119	-119.82	32.51211	0.091
3	0.0697289	0.1525919	0.313	100.98	85.22844	0.416
5	0.0194544	0.3261092	0.717	97.59	195.37674	0.060
6	0.0240682	0.4335031	1.000	141.38	272.52243	0.055
7	0.0220834	0.4775853	0.056	0.20	15.15163	0.046
9	0.0247486	0.6913506	0.134	178.90	36.59633	0.036
10	0.2080725	0.7380273	0.526	150.20	143.35895	0.271

**PRONY S-TABLE FOR PRS NUMBER 2: TSPAN = [8.85, 34.35]
*SIGNAL-TO-NOISE RATIO = 32.0990 FOR NMODES = 58

MODE	DAMPING	FRQ (HZ)	REL WT	PHASE	AMPLITUDE	%DAMPING
1	0.0834551	0.0000000	0.156	0.00	42.21979	1.000
2	0.0012950	0.0319732	0.105	-101.06	28.54146	0.040
3	0.0662984	0.1444761	0.273	126.71	74.04310	0.417
5	0.0194309	0.3260021	0.702	121.54	190.45377	0.059
6	0.0244424	0.4335056	1.000	173.05	271.27151	0.056
7	0.0263345	0.4800066	0.064	16.79	17.38064	0.055
9	0.0248133	0.6913127	0.131	-131.18	35.52674	0.036
10	0.2017824	0.7157755	0.404	-146.40	109.57405	0.271

**PRONY S-TABLE FOR PRS NUMBER 3: TSPAN = [9.05, 34.55]
*SIGNAL-TO-NOISE RATIO = 31.6030 FOR NMODES = 58

MODE	DAMPING	FRQ (HZ)	REL WT	PHASE	AMPLITUDE	%DAMPING
1	0.0938802	0.0000000	0.148	0.00	38.05296	1.000
2	-0.0015441	0.0323902	0.083	-94.25	21.43110	-0.048
3	0.0693897	0.1496846	0.288	128.16	74.14603	0.421
5	0.0194548	0.3260746	0.722	144.69	186.17179	0.060
6	0.0242376	0.4333762	1.000	-155.54	257.83134	0.056
7	0.0251606	0.4759581	0.069	69.68	17.66452	0.053
9	0.0252325	0.6914552	0.138	-81.62	35.48735	0.036
10	0.2382083	0.7391455	0.354	-104.14	91.20901	0.307

**PRONY S-TABLE FOR PRS NUMBER 4: TSPAN = [9.25, 34.75]
*SIGNAL-TO-NOISE RATIO = 29.6770 FOR NMODES = 58

MODE	DAMPING	FRQ (HZ)	REL WT	PHASE	AMPLITUDE	%DAMPING
2	-0.0038375	0.0339231	0.064	-94.61	17.00587	-0.112
3	0.0757598	0.1231937	0.340	-176.38	89.80358	0.524
5	0.0196893	0.3258386	0.702	169.30	185.49640	0.060
6	0.0246890	0.4345596	1.000	-128.18	264.42666	0.057
9	0.3208073	0.6669533	0.587	-53.51	155.28208	0.433
10	0.0246291	0.6906581	0.127	-29.69	33.65391	0.036

Table I. PRS locus for 4 sliding-window fits to PG&E ringdown #1

of the Prony method. The display has been "trimmed" to show only the modes having a strength greater than 0.05, relative to the strongest mode in a declared frequency window extending from FTRIML to FTRIMH (0.0 and 2.0 Hz respectively). The final order of the raw model returned by the Prony solution code is determined by the rank of the signal together with logic designed to make the model "parsimonious". The quantity NMODES is the sum of all modes, both real and complex.

The modal frequencies are displayed in Hz, or $\omega/(2\pi)$; for consistency, the damping is displayed as $-\sigma/(2\pi)$. The percentage damping is $-\sigma/(\sigma^2+\omega^2)^{1/2}$, expressed as a decimal fraction. The amplitude and phase are parameters A_i and Φ_i in equation (5D). Note that there are cases in which the signal component produced by mode i does not actually reach level A_i within the time span of the record. These are characterized by a strong damping, fairly high frequency, and an initial phase making $\cos\Phi_i$ small.

Such sliding-window solutions are useful for detecting changing signal characteristics (due perhaps to nonlinearities or hidden inputs), and for distinguishing essential modes from those that are mere accessories to the fitting process. Table I shows 2 modes that may be in this category, near 0.72 Hz for solutions 1-3 and near 0.67 Hz for solution 4. The other modal estimates displayed there seem acceptably consistent.

VI. CONSTRUCTION OF IMPULSE RESPONSE MODELS

This section addresses the problem of constructing impulse response models from ringdown signals or from the corresponding frequency response data. Such models provide added insight into the underlying system dynamics, and they are a basic requirement for most control system design procedures. In the present circumstances they are also useful for validating results from SIGPAKZ against those produced by other methods.

BPA's SYSFIT program [2] has been effective for direct fitting of models to measured frequency response, but good results sometimes call for considerable user expertise. The severe non-convexity [14] of the associated optimization problem requires a reasonable starting point for the solution search, plus a suitable model order.

Information concerning the poles and the order of the model is directly available in the PRS. The residues -- or, equivalently, the zeros -- of the PRS reflect the characteristics of the applied signal, however, and are not those of the impulse response model. Also, because Prony analysis must start after the input is removed, the feedforward coefficient D in equation (5A) is not contained in the PRS. The corresponding jump Du(t), while directly available in computer simulations, is not readily measured in the field. Present BPA instrumentation also leaves some doubts as to the exact time of brake application. These data defects can be alleviated through supplemental use of SYSFIT.

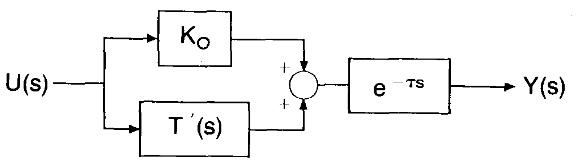

Figure 8. SYSFIT model for ringdown frequency response

Figure 8 shows the SYSFIT model structure used for fitting frequency response data such as that in Figures 3A,B. Transfer function T'(s) is strictly proper, (i.e., having more poles than zeros), and K_O is the feedforward coefficient corresponding to D. Time delay τ results from misjudging the point in the record at which the test signal was applied.

Figures 9A,B show fits to the response data of Figure 4, for brake pulse #1. The starting data used for T'(s) was that of the PRS signal model, according to equations provided in [15]. The model (exclusive of the delay block) was left in block parallel form during the fitting process, with the poles fixed at their initial values. Subsequent conversion to cascade form produced the parameters in Table II. The test pulse is estimated at a point about 0.30 seconds later than initially thought. Figure 10

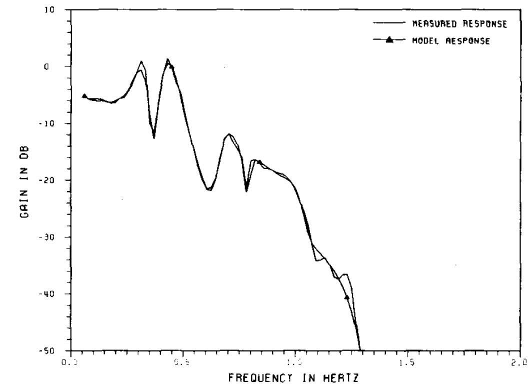

Figure 9A. Gain fit to PG&E response #1, 04/18/89 (SYSFIT model)

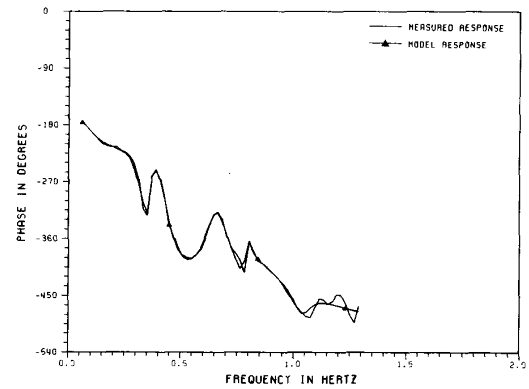

Figure 9B. Phase fit to PG&E response #1, 04/18/89 (SYSFIT model)

ZEROS			POLES		
0.76967859E-02			-0.52766866E-01		
-0.28556412E-02	± J*	0.22105882E+00	-0.30809125E-02	± J*	0.33609590E-01
-0.11362195E-01	± J*	0.36056503E+00	-0.69728854E-01	± J*	0.15259190E+00
-0.24605906E-01	± J*	0.47060961E+00	-0.24703690E-02	± J*	0.22081395E+00
-0.49166661E-01	± J*	0.60953387E+00	-0.19454352E-01	± J*	0.32610920E+00
-0.58528603E-01	± J*	0.67871977E+00	-0.24068154E-01	± J*	0.43350312E+00
-0.22636442E-02	± J*	0.78648730E+00	-0.22083414E-01	± J*	0.47758529E+00
-0.46589538E-01	± J*	0.10529314E+01	-0.24748638E-01	± J*	0.69135060E+00
-0.17425601E-02	± J*	0.13182110E+01	-0.20807250E+00	± J*	0.73802730E+00
-0.65951915E-01	± J*	0.17323784E+00	-0.87919202E-02	± J*	0.78800546E+00
-0.18417704E-01	± J*	0.25651364E-01	-0.46236811E-01	± J*	0.10180450E+01

GAIN = -0.58628492E-01 MW/MW
DELAY = 0.29959583E+00 SECOND

Table II. Parameters for SYSFIT model

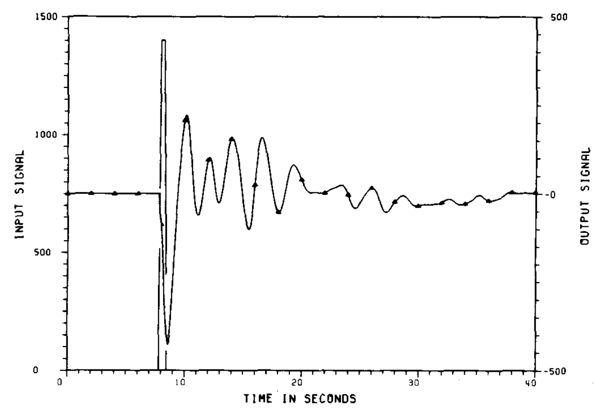

Figure 10. Response of SYSFIT model to simulated brake test

shows response of the SYSFIT model to a simulated brake energization. This is a reasonable match to the actual system response (Figure 11), even though the model has not been subjected to customary refinements.

In [15] relations are developed for recovering the parent impulse response model from the PRS, under the assumption that the signal was produced by a known pulse input. Using these relations together with the coupling and pulse timing estimates provided by SYSFIT yields a model which responds as shown in Figure 12. The results seem superior to those of the SYSFIT model, even though K_0 is not represented. This should not be expected when strong voltage coupling requires large K_0. In such cases it is advisable to accurately determine the associated signal discontinuities during the test itself.

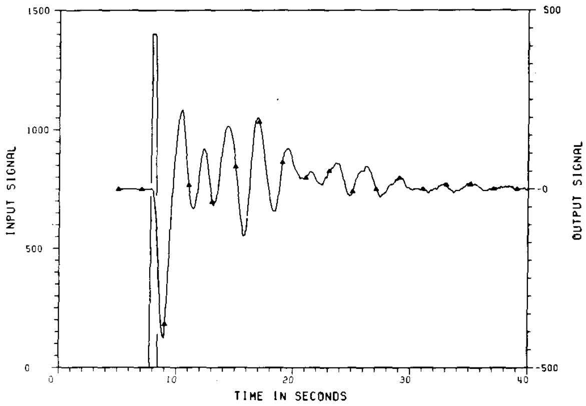

Figure 11. PG&E ringdown #1, 04/18/89

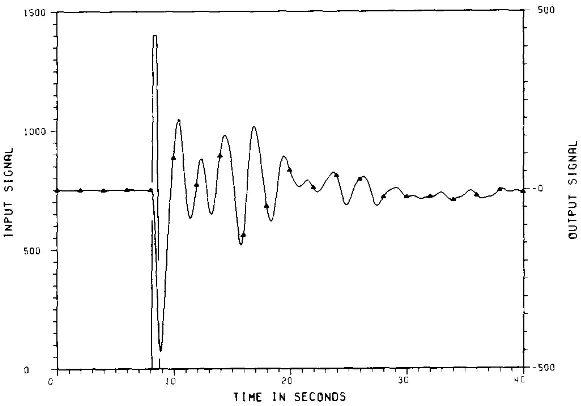

Figure 12. Response of PRS impulse model to simulated brake test

Frequency response of the PRS model, with adjustments, is compared against FFT results in Figures 13A and 13B. A reasonable match is produced even by the "raw" PRS model, for which K_0 is neglected and there is a zero slightly into the right half of the s-plane (near 0.78 Hz). The stronger peaks and valleys for the PRS model are probably caused by Hanning of the record submitted to FFT analysis, and by noise removal in the Prony analysis. The match is improved by using the SYSFIT value of the K_0 (equal to the gain in Table II), and by reflecting the RHP zero into the LHP.

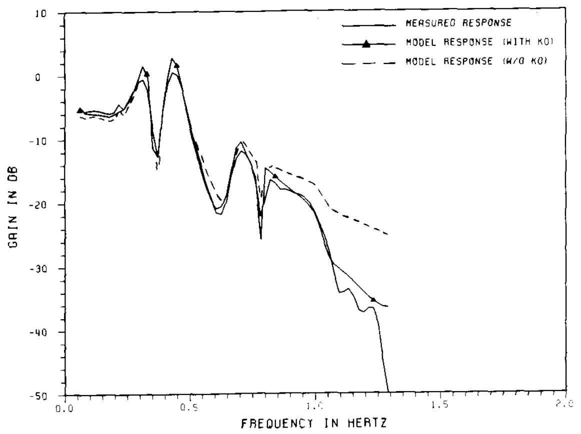

Figure 13A. Gain fit to PG&E response #1, 04/18/89 (PRS model).

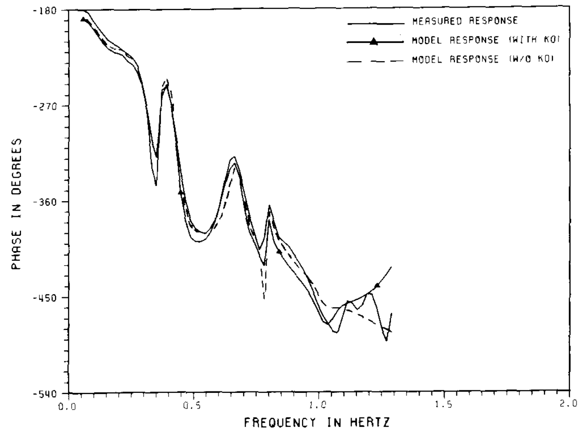

Figure 13B. Phase fit to PG&E response #1, 04/18/89 (PRS model).

VII. CONCLUSIONS

Results presented in [1] demonstrate that Prony analysis can be very effective in response based modal analysis of noise-free LTI systems. Results for stability program output signals seemed realistic, for "small-signal" cases, and will be tested against the Ontario Hydro eigenanalysis programs [16]. Large-signal cases involve significant nonlinearities and may require LTV characterizations. Firm guidelines in this respect will require better insight into system behavior. Prony analysis, in some extended form, may play a major role in their development.

This paper has gone beyond modal analysis to the construction of standard form impulse response models for use in extended analysis and in control system design. SIGPAKZ has been applied to signals obtained through large-scale system tests, in a signal environment characterized by a high noise level and by uncertainties due to unmeasured system inputs. Accessory use was made of SYSFIT, to estimate D in the output y=Cx+Du and to refine record timing. Again, the results seem realistic. The associated models reproduce the observed system response well, especially when the noise characteristics are considered. Means for projecting and mitigating the impact of system noise upon PRS accuracy are being investigated.

Ultimately, solving the noise problem in system tests may also solve the problem of LTV modeling for nonlinear signals. Both situations favor use of the shortest possible record length -- to focus analysis upon record segments where the signal is well above the noise, or to minimize the changes in system dynamics. In principle, the requisite information base is available in a properly chosen collection of simultaneous signals. The feasibility of developing a multi-output version of the Prony method for extracting this information is being explored with members of the signal processing community.

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REFERENCES

[1] J.F. Hauer, C.J. Demeure, and L.L. Scharf, "Initial Results in Prony Analysis of Power System Response Signals," IEEE Trans. Power Systems, pp. 80-89, February 1990.

[2] J.F. Hauer, "Power System Identification by Fitting Structured Models to Measured Frequency Response," IEEE Trans. PAS, pp. 4918-4925, December 1981.

[3] G.R.B. Prony, "Esssai Experimental et Analytic ...," J. de L'Ecole Polytechnique (Paris); Vol. 1, pp. 24-76, 1795.

[4] S.M. Kay and S.L. Marple, "Spectrum analysis--a modern perspective," Proc. IEEE, pp. 1380-1419, November 1981.

[5] R. Kumaresan and D.W. Tufts, "Estimating the parameters of exponentially damped sinusoids and pole-zero modeling in noise," IEEE Trans. Acoustics, Speech, and Signal Processing, pp. 833-840, December 1982.

[6] R. Kumaresan, L.L. Scharf, and A.K. Shaw, "An algorithm for pole-zero modeling and spectral analysis," IEEE Trans. Acoustics, Speech, and Signal Processing, pp. 637-640, June 1986.

[7] J.F. Hauer, "BPA Experience in the Direct Measurement of Power System Dynamics," American Power Conference, Chicago, Il, April 23-25, 1990. Paper 35b.

[8] J.F. Hauer and R.L. Cresap, "Measurement and Modeling of Pacific AC Intertie Response to Random Load Switching," IEEE Trans. PAS, pp. 353-359, January 1981.

[9] J.F. Hauer, "Robust Damping Controls for Large Power Systems," IEEE Control Systems Magazine, pp. 12-19, January 1989.

[10] T. Kailath, Linear Systems. Prentice-Hall: Englewood Cliffs, 1980.

[11] C.J. Demeure, "Fast Algorithms for Linear Prediction and Modal Analysis," Ph.D. Dissertation, ECE Dept., University of Colorado, Boulder, 1988.

[12] C.J. Demeure, "Fast QR Factorization of Vandermonde Matrices," to appear in the J. Linear Algebra and Applications, Special Issue on Linear Systems and Control, Spring 1989.

[13] J.S. Bendat and A.G. Peirsol, Random Data: Analysis and Measurement Procedures. Wiley-Interscience: New York, 1971.

[14] M. Avriel, Nonlinear Programming - Analysis and Methods. Prentice-Hall: Englewood Cliffs, N.J., 1976.

[15] J.F. Hauer, "The Use of Prony Analysis to Determine Modal Content and Equivalent Models for Measured Power System Response," Eigenanalysis and Frequency Domain Methods for System Dynamic Performance, IEEE Publication 90TH0292-3-PWR, pp. 105-115.

[16] D.Y. Wong, G.J. Rogers, B. Porretta, and P. Kundur, "Eigenvalue Analysis of Very Large Power Systems," IEEE Trans. Power Systems, pp. 472-480, May 1988.

BIOGRAPHY

John F. Hauer (S'59-F/90) was born in Washington State in 1936. He received the B.S. degree (summa) at Gonzaga University in 1961, and the Ph.D. degree at the University of Washington as a National Science Foundation Graduate Trainee in 1968. Both were in electrical engineering.

In 1961 and 1962 he was with the General Electric Company, working in the area of nuclear reactor controls while enrolled in the Advanced Engineering Training Program. In 1963 and 1964 he developed spacecraft navigation and guidance methods at the Boeing Company, for use in Lunar Orbiter design and mission control. His subsequent doctoral research addressed methods for designing safety factors into thrusting trajectories for interplanetary flight. From 1968 to 1975 he was a member of the Computing Science faculty at the University of Alberta, where he became an associate professor in 1972. His teaching responsibilities and research activities there centered upon constrained optimization of dynamic systems. Since 1975 he has been with the Bonneville Power Administration. His work there deals with the identification, analysis and control of power system dynamics.

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