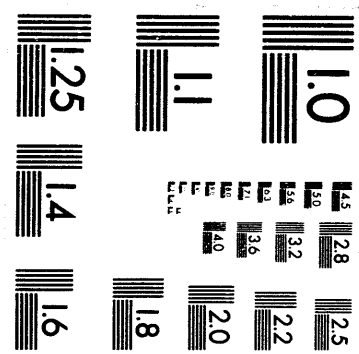

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A PROCEDURE FOR OSCILLATORY PARAMETER IDENTIFICATION

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A Procedure for Oscillatory Parameter Identification

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Abstract -- **A procedure is proposed where a power system is excited with a low-level pseudo-random probing signal and the frequency, damping, magnitude, and shape of oscillatory modes are identified using spectral density estimation and frequency-domain transfer-function identification. Attention is focussed on identifying system modes in the presence of noise. Two example cases are studied: identification of electromechanical oscillation modes in a 16-machine power system; and turbine-generator shaft modes of a 3-machine power plant feeding a series-compensated 500-kV network.**

Keywords -- Electromechanical oscillations, torsional oscillations, parameter identification, field tests, Prony analysis.

I. INTRODUCTION

There is a broad effort in the utility industry to operate existing transmission systems at higher levels. This may result in poor system dynamic characteristics. To reliably operate under these conditions, the industry is turning to advanced large-scale control devices to maintain stability. A prime example is the Flexible AC Transmission Systems (FACTS) program [1]. A major component of developing power-system dynamic controllers involves field testing devices. This includes both tuning and commissioning tests. Examples, other than FACTS-type devices, include field tuning power system stabilizer (PSS) units [2], studying fault-response data to determine interarea electromechanical dynamic characteristics [3,4], and investigating torsional oscillation and subsynchronous effects [1,5]. As large-scale control devices are integrated into a system, field testing will become extremely critical to assuring reliable operation. An important component to field testing is determining how certain devices affect the frequency, damping, magnitude, and phase of critical oscillation modes (both for electromechanical dynamics and subsynchronous resonance problems). In this paper, we propose a test procedure for estimating system modes. The procedure is designed to perform well under conditions often encountered in the field (such as noisy data).

Considerable work has been conducted on fitting linear models to oscillatory ringdown data using Prony analysis and other time-series techniques [3-9]. The objective of these techniques is to identify the modal content of the ringdown. All of these approaches require the modes to be excited with a pulse-type function. To obtain accurate estimates, the modes must be excited well above the natural noise present in the system. Such tests can be conducted only under strict safety conditions.

The procedure proposed in this paper uses a different approach for excitation. It involves exciting the system with a low-level pseudo-random probing signal (possibly for several minutes) and identifying oscillatory modes using spectral density estimation and frequency-domain transfer-function identification. It is shown that the system only needs to be excited slightly above the natural system noise; therefore, causing little stress on the system. Two example cases are studied: the identification of electromechanical oscillation modes of a 16-machine power system; and the turbine-generator shaft modes of a 3-machine power plant feeding a series-compensated 500-kV network. In both cases, the problem of identifying the modes under noisy conditions is considered.

The identification approach in this paper is similar to the one demonstrated in [10] but with several extensions. In [10] a random binary signal is used to excite the dynamics of a generator. A discrete Fourier transform (DFT) is then used to estimate the system's frequency response. In this paper we use auto and cross spectral estimation to calculate the frequency response because it provides much more accurate estimation; we then use system identification techniques to estimate the system modes.

II. GENERAL PROBLEM

Consider the general system in Fig. 1. $u(t)$ is a probing signal at time t used to excite the system modes; $n_p(t)$ is

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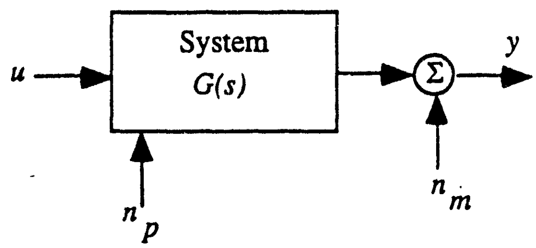

Fig. 1. General system model.

unknown process noise that also excites the system modes; $n_m(t)$ is unknown measurement noise; and $y(t)$ is the measured signal. The process noise represents the many random factors that constantly excite the system modes under ambient conditions; these include varying load and generation effects, system switching effects, and small disturbances. n_m represents the noise associated with measurement devices. The objective here is to apply a low-level pseudo-random probing signal at u and measure the response y and estimate the linearized system transfer function that includes the modes. In most cases, measurement noise can usually be mitigated through filtering and instrumentation refinements. Process noise, on the other hand, is more difficult to handle because it produces energy in the same bandwidth that is to be identified.

Process noise effects are demonstrated by studying the field data shown in Fig. 2. Fig. 2 shows the ringdown response on a 500 kV transmission line in the western U. S. power system following a system disturbance (measured by the Bonneville Power Administration (BPA)). Frequency analysis shows that the pre-disturbance and post-ringdown ambient noise has energy peaks at the same frequencies contained in the ringdown. This indicates that there are underlying processes (such as random load switching) in the system which are continuously exciting system modes. When using standard ringdown analysis [3], the process noise can cause errors in the estimated modal terms if the initiating pulse is not of sufficient strength. Most often the errors are in the estimated damping [11].

In applying the procedure in this paper, it is assumed that the system and noise effects are stationary. This implies that the steady-state operating conditions of the power system do not significantly change over the data collection interval. For some cases, this assumption is only valid for several minutes of operation. Past this time frame, area generation control, load switching, and network changes are more likely to occur, all of which can alter the dynamic response and noise characteristics of the system. Fortunately, qualitative analysis can be performed on data collected over a few minutes for electromechanical problems and for several seconds for torsional shaft problems.

In the simulation results presented later in this paper, Gausian noise colored with a fractal filter is used as the

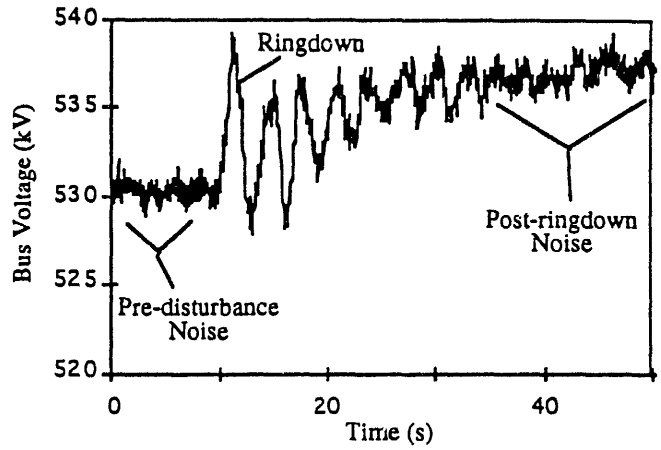

Fig. 2. Malin-Round Mountain voltage measured during a March 14, 1993 disturbance.

process noise and Gausian white noise is used as the measurement noise. The development of these characteristics are discussed in [12].

III. Identification Procedure

The identification procedure is designed to reduce the effects of process and measurement noise by using a pseudo-random excitation and spectral estimation. This allows for accurate modal identification at low signal-to-noise ratios (SNRs). The identification procedure is conducted using the following steps:

1. Apply u to excite the frequency range of interest and measure y. Using u and y, estimate the system's frequency-response transfer function $G(j\omega)$ and call this estimate $G_e(j\omega)$.

2. Fit a parametric model to $G_e(j\omega)$ using either Prony analysis or frequency-domain fitting. The parametric model will then contain the identified modes.

A. Estimating $G(j\omega)$

In estimating $G(j\omega)$, a few definitions are required: $U(j\omega)$ is the Fourier transform of u; $S_{uy}(\omega)$ is the cross spectral density between u and y; and $S_{uu}(\omega)$ is the auto spectral density function for u. Using standard probability theory [13], we know that

$$S_{uy}(\omega) = \mathrm{E}\{U^*(j\omega)Y(j\omega)\} \tag{1}$$

$$S_{uu}(\omega) = \mathrm{E}\{U^*(j\omega)U(j\omega)\} \tag{2}$$

where $\mathrm{E}\{\cdot\}$ represents the expectation operator.

Let $G(s)$ represent the linearized Laplace-domain transfer function of the system in Fig. 1. Also, assume that u is uncorrelated with n_p and n_m; and that u, n_p, and n_m are stationary (this is a safe assumption because the user has complete control over u). Then the frequency response of $G(s)$ can be obtained from [13]

$$G(j\omega)=\frac{S_{uy}(\omega)}{S_{uu}(\omega)} \tag{3}$$

Using finite-length noisy records, S_{uy} and S_{uu} cannot be exactly calculated, but they can be estimated using the well-established periodogram averaging method (often termed the Welch method [14]). Let u_k be a sampled version of $u(t)$ with sample period T and $k = 0,1,...,N-1$. Then S_{uu} is estimated by S^e_{uu} where

$$S^e_{uu}(\omega)=\frac{T}{WK}\sum_{i=1}^{K}\left\{\left|\mathrm{DFT}(w_M u^{(i)})\right|^2\right\} \tag{4a}$$

$$W=\frac{1}{M}\sum_{k=0}^{M-1}w_M^2(k) \tag{4b}$$

where u is broken up into K subsets all of length M (these subsets are allowed to overlap and the ith subset is called $u^{(i)}$), w_M is a windowing function (such as a Hanning window [14]), and DFT stands for the discrete Fourier transformation. S^e_{uy} is calculated similar to S^e_{uu}. The frequency response of the transfer function is then estimated using

$$G_e(j\omega)=\frac{S^e_{uy}(\omega)}{S^e_{uu}(\omega)} \tag{5}$$

Several trade-offs exist between the various parameters (N, M, the amount of overlap between windows, and the characteristics of u). The objective in choosing these parameters is to make $G_e(j\omega)$ accurately represent $G(j\omega)$ in the frequency range of interest. The quality of $G_e(j\omega)$ is judged using the coherency function, defined as [13]

$$\gamma^2_{uy}(\omega)=\frac{\left|S^e_{uy}(\omega)\right|^2}{S^e_{uu}(\omega)S^e_{yy}(\omega)} \tag{6}$$

If $G_e(j\omega)$ is accurate, $\gamma_{uy}{}^2$ will be close to 1. If $\gamma_{uy}{}^2$ is not close to 1, parameters N, M, window overlap, and possibly the probing signal u are adjusted. If $\gamma_{uy}{}^2$ takes on a random form, then N should be increased or the strength of u can be increased. If $\gamma_{uy}{}^2$ falls away from 1 over a frequency range where $G(j\omega)$ has a peak or valley, this indicates that M should be increased. Parameter values that work well with electromechanical oscillation and shaft torsional problems are discussed in the following sections.

B. Parameter Identification

Given $G_e(j\omega)$, a parametric model is identified using one of two approaches. With the first, an inverse discrete Fourier transformation (IDFT) operation is used to estimate the impulse response of $G(s)$ in the frequency range of interest, and Prony analysis is used to fit a model. With the second approach, the fitting is applied directly to $G_e(j\omega)$. From the authors' experience, both approaches provide similar results.

Prony analysis has been extensively discussed in recent power system literature relating to analysis of ringdown and impulse response data [6-8]. Essentially, it is a numerical technique by which a signal is least-squares fitted to a weighed summation of complex exponentials [15]. Its uses in transfer function identification have been demonstrated [7,16], and, therefore, will not be repeated here.

Several methods have been proposed for fitting a parametric model to the frequency response of a system. An extensive literature review is contained in [12]. The method used by the authors involves fitting a transfer-function model to the frequency-response data in a least-squares sense. The approach is described in detail in [17], which is a variation of the approaches contained in [18] and [19].

IV. Electromechanical Mode Identification

In this section, we demonstrate how one can apply the proposed identification approach to identify electromechanical oscillation modes. Consider a PSS tuning problem with the objective being to identify a transfer function for the generator. In past work, this problem has been approached by applying a pulse signal to the reference voltage of the machine and analyzing the resulting ringdown [7]. To obtain accurate identification under noisy field conditions, a relatively large pulse must be used. If the pulse is excessively large, the generator's excitation system will saturate, causing a nonlinear response that results in poor identification. Also, under poor stability conditions, this test is risky because it can cause the generator to significantly oscillate. The identification approach proposed here is a natural alternative because accurate identification can be achieved with a significantly lower probing signal. The trade-off is that the test requires up to a few minutes while a pulse test requires several seconds.

The Fig. 3 test system is taken from [7]. Two types of generators are modeled in the system. One type has large power generation and inertia (shaded circles); these represent an aggregate of smaller machines that swing together at an interarea mode. These generators are modeled as classical machines. The remaining 10 generators are represented using standard detailed two-axis models and full exciter models.

The objective is to identify a reduced-order transfer function between the reference voltage summing block, where the PSS is connected, and the accelerating power of generator 2. Four modes are controllable and observable from this generator: generator 2's local mode; generators 3's local mode; and two interarea modes. Two identification approaches are considered. With the first, a pulse input is used as the probing signal, as done in [7]; with the second, a pseudo-random signal band-limited between 0 and 5 Hz is used. Process and measurement noise is simulated by adding noise to generator 2's terminal voltage and measured accelerating power. Tests are conducted by using the noise-free model identified in [7] as $G(s)$ in Fig. 1.

Fig. 4 shows the two probing signals. The pseudo-random probing signal is applied for 3.4 minutes and the analysis parameters are N = 4096, M = 1024, 90% overlap, and T=0.05 s. This represents a signal-to-noise ratio (SNR) of 12 dB for the process noise and 33 dB for the measurement noise. The pulse-probing signal has an amplitude of 0.05 p.u. voltage (an effective SNR of 25 dB at the output). Fig. 5 shows that the output for pseudo-random probing is much less than for pulse probing resulting in less generator stress.

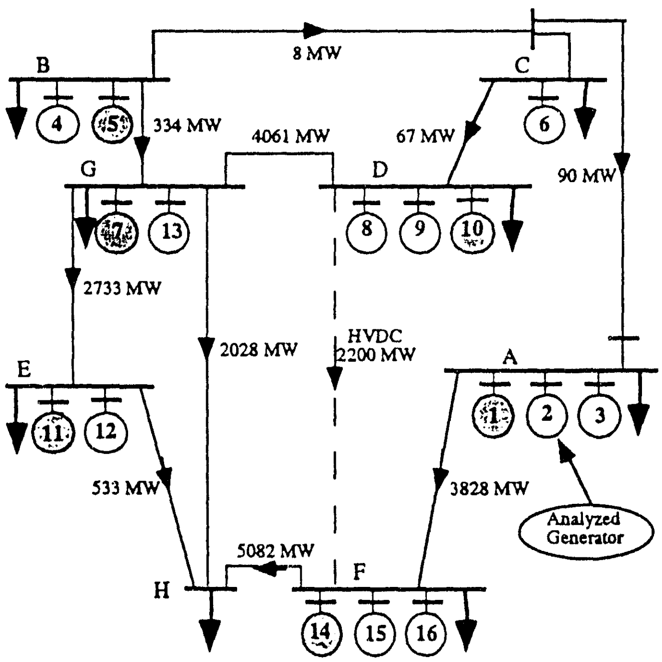

Fig. 3. 16-machine test system.

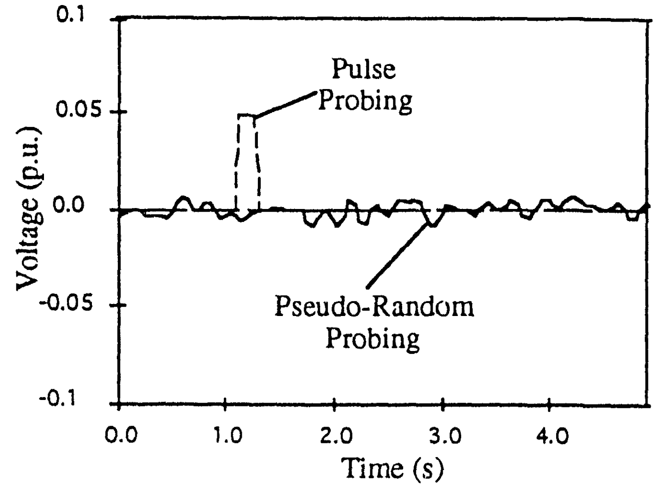

Fig. 4. Probing signals added to generator 2's reference voltage.

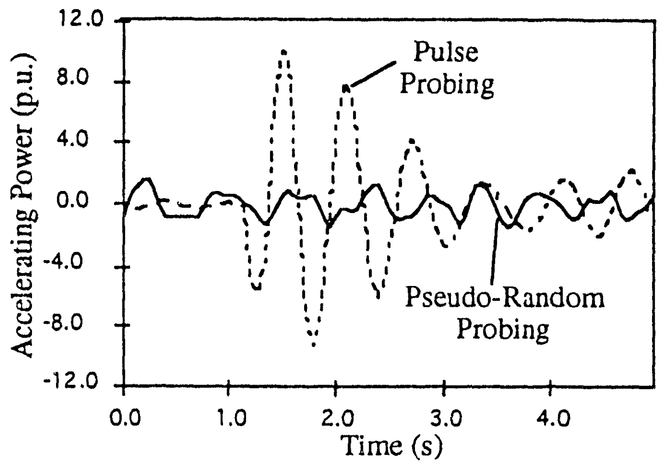

Fig. 5. Generator 2's response to probing signals and noise.

TABLE I
IDENTIFIED MODES FOR GENERATOR 2 SYSTEM.

Actual (Hz)	Pseudo-random probing	Pulse probing
-0.0716 +j1.56	**-0.0718 +j1.56**	**-0.0431 +j1.56**
-0.0762 +j1.81	-0.0769 +j1.82	-0.0882 +j21.0
-0.00477 +j0.688	-0.00777 +j0.686	-0.00684 +j0.690
-0.0261 +j0.361	-0.0337 +j0.361	-0.0296 +j0.360

Table I shows the identified modes and Fig. 6 shows the frequency response of the identified transfer functions compared to the actual response. The bolded mode in Table I is the local mode of generator 2. This mode dominates the response and, in most cases, would be the primary mode the

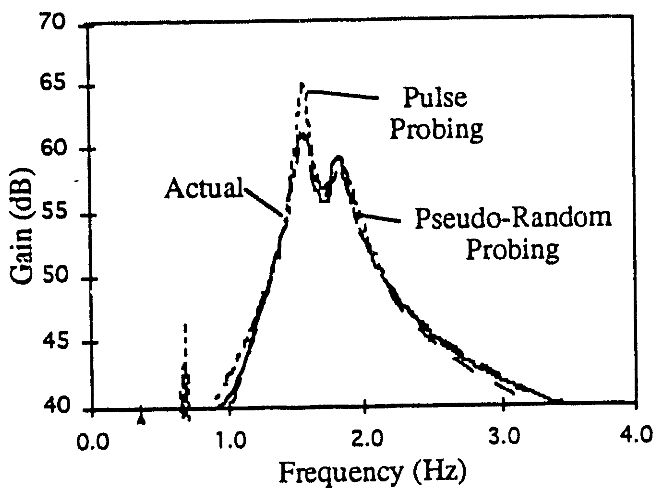

Fig. 6. Frequency-response of identified models from pulse and pseudo-random probing versus the actual response.

PSS would be designed to dampen. With pseudo-random probing, more accurate identification is achieved than with pulse probing. This is especially apparent on generator 2's local mode. To obtain more accurate results with pulse probing, the strength of the signal would need to be increased, causing more stress and possible exciter saturation.

V. Torsional Mode Identification

Now we demonstrate the feasibility of the proposed approach in identifying turbine-generator shaft oscillation modes of a large synchronous generator. Tests are conducted on a computer-simulated three-machine system. A dynamic brake is connected to the low-voltage terminals of one machine and is used to excite the machine's torsional modes (see [5] for a complete description). Two closely spaced modes are identified by exciting the system for several seconds with a pseudo-random band-limited probing signal at the brake. Process and measurement noise are simulated by adding computer-generated noise at appropriate locations in the system (this noise is assumed unknown to the algorithm). It is demonstrated that modes can be accurately identified even at SNRs near 0 dB.

Fig. 7 shows a simplified diagram of the test system. The system contains three synchronous machines: two parallel 500-kV series-compensated backbone transmission lines and a 230-kV local transmission system with external system equivalents. Two machines, C1 and C2, are identical 377-MVA generators feeding the 500-kV lines through an autotransformer. Machine C3 is rated at 818 MVA and feeds the 500-kV bus directly. Six masses are connected to the shaft of C3, a high-pressure turbine, an intermediate-pressure turbine, 2 low-pressure turbines, a rotating exciter, and the synchronous generator. These masses create four dominant torsional modes on the shaft [5]. The dynamic brake is applied to the low-voltage terminals of C3.

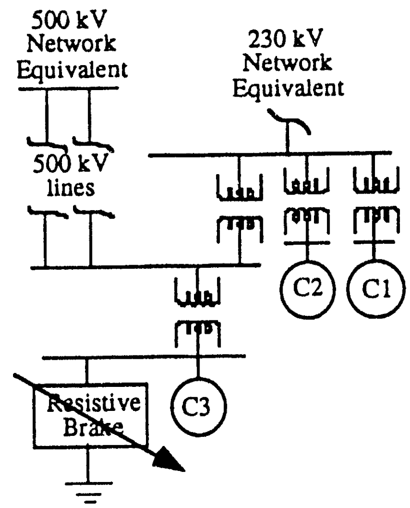

Fig. 7. Torsional mode test system.

Table II summarizes the modes for the test system. These modes were identified by fitting a 10th-order transfer function between the brake and the generator speed deviation signal $\Delta\omega$. A value of unity on the control input signal ($u(t)$) is equivalent to 100 MW of resistive braking at the generator terminals. The speed deviation is measured at the generator mass (the rotor). In [5], Prony analysis was used to identify the transfer function from the simulated system under noise-free conditions.

The effectiveness of the proposed identification process is tested by performing fits under noisy conditions. The noise-free model is used as the system ($G(s)$) representing Fig. 1. Process noise is simulated by adding noise to the brake input, which excites the torsional modes to be identified. Measurement noise is added to $\Delta\omega$. Both of these noise sources are unknown to the fitting algorithm.

The objective of the experiment is to identify the frequency and damping of the 18 and 21 Hz modes under noisy conditions. Fig. 8 shows the system response with and without probing. In the no probing case, the output is caused by the process and measurement noise. With probing, the output is caused by both probing and noise. Note that the probing signal is large enough to just slightly excite the system above ambient conditions. This probing signal represents a SNR of 0 dB for the process noise and 20 dB for the measurement noise. To excite only the 18 and 21 Hz modes, the frequency response of the probing signal is sharply band-limited between 15 and 25 Hz. Two parameter

TABLE II
TORSIONAL SHAFT MODES (Hz).

Electromechanical mode	$-0.0544 + j\ 1.04$
Torsional mode A	$-0.0383 + j\ 10.3$
Torsional mode B	$-0.621 + j\ 18.7$
Torsional mode C	$-0.0412 + j\ 21.0$
Torsional mode D	$-0.119 + j\ 45.9$

cases are considered: 1) $N = 32000$, $M = 2048$, 75% window overlap; and 2) $N = 131023$, $M = 8192$, 75% overlap. For both cases $T = 0.005$ s.

Fig. 9 shows the actual frequency response versus that estimated for the two cases. From Fig. 9, one would say that both cases accurately estimated the frequency response. Fig. 10 shows the coherency functions for both cases. Note that with case 2, the function is closer to 1 indicating a more accurate estimate of $G(j\omega)$. The coherency for case 2 is closer to 1 because more accurate resolution is obtained as a result of the larger window size (i.e., larger M).

To use Prony analysis to estimate the system modes, the impulse response is calculated using an IDFT of the estimated frequency response. In calculating the IDFT, the frequency response outside the 15 Hz to 25 Hz range is ignored by assuming it to be 0 because the probing signal does not excite this range. Table III shows the estimated modes. Because case 2 uses more data to estimate the system's frequency response, it identifies the modes more accurately. But, the modes are still identified relatively accurate in case 1.

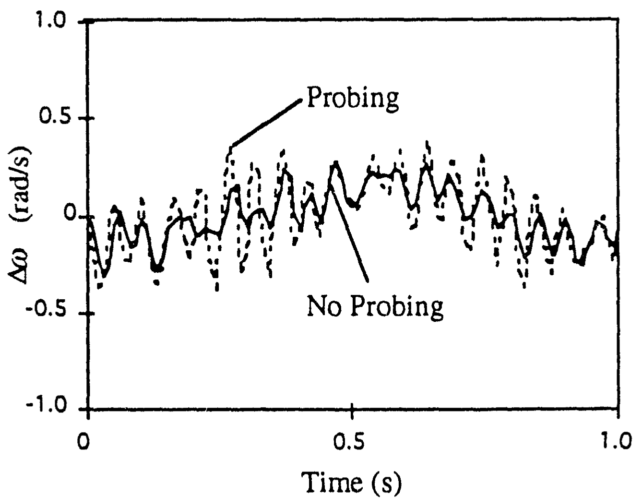

Fig. 8. Torsional system response to probing.

TABLE III
IDENTIFIED MODES FOR TORSIONAL SYSTEM (Hz).

Actual	Case 1	Case 2
-0.0621 +j18.7	-0.0719 +j18.7	-0.0655 +j18.7
-0.0412 +j21.0	-0.0658 +j21.0	-0.0407 +j21.0

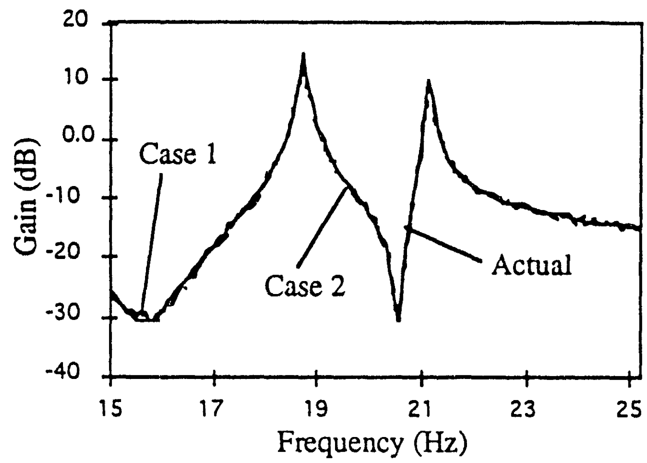

Fig. 9. Actual torsional system frequency response versus estimated for cases 1 and 2.

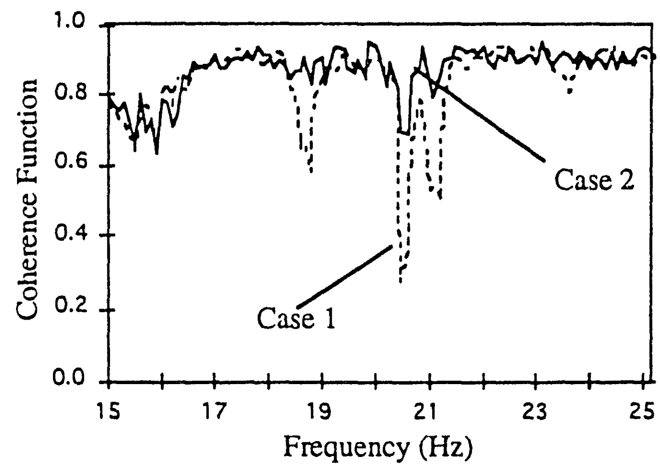

Fig. 10. Coherency functions for torsional system cases.

VI. CONCLUSIONS AND FUTURE WORK

A method has been proposed where a low-level pseudo-random signal is applied to a power system with the objective of identifying critical system oscillation modes. The approach allows accurate identification with low signal-to-noise ratios. Also, the use of the low-level excitation prevents, to a certain extent, the system from entering nonlinear regions that make identification difficult (such as the saturation of an exciter). It has been demonstrated that the method results in more accurate mode identification than pulse-type probing under noisy conditions.

Applying the technique for identifying electromechanical oscillation modes requires the system to be excited for a few minutes with a low-level probing signal. The advantage is that the probing signal can be very low level. For PSS applications, this avoids having to overly excite the system causing stress and possible saturation of the excitation system.

In applying the method to a computer-simulated problem, it is demonstrated that the modal characteristics of a torsional shaft oscillation can be accurately identified by exciting the system for several seconds at a SNR of 0 dB or greater. Through band-limited excitation, modes in a specific frequency range can be identified, without exciting modes outside that range.

Two areas merit future investigation. The first involves applying this approach in the field. The second area involves using the method to identify specific model parameters, such as the inertia of a generator or exciter time constants.

VII. ACKNOWLEDGEMENT

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Dr. Hauer is a member of the IEEE Power Engineering and Control Systems societies.

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