APPLICATION OF SYSTEM IDENTIFICATION TECHNIQUES TO AN RF CAVITY TUNING LOOP

L. K. Mestha
Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue, Dallas, Texas 75237, USA

and

C. W. Planner
Rutherford Appleton Laboratory, Chilton, Didcot, OXON OX11 OQX, UK

ABSTRACT

Modern system identification is applied to rf cavity tuning on the ISIS synchrotron. Four types of test signals are investigated to assess their suitability for real time measurement in an accelerator environment. The Pseudo Random Binary Signal (PRBS) appears to be the most advantageous. Measurements under normal operating conditions allow automatic identification for a self adapting loop. The interactive software MATLAB is used to process the data and the identified model is represented in pole-zero form. The model shows good correlation with system performance.

INTRODUCTION

The ISIS RF systems[1] incorporate control loops for voltage, frequency, phase, inter-cavity phase and beam loading compensation. The analogue frequency tuning loop could not reach the required accuracy and was augmented by a digital loop (Figure 1). The design of the digital loop required gain and phase measurement over the frequency band and the representation of the response in a concise mathematical form. This process is known as system identification.

The conventional approach to system identification is to measure the response to a sinusoidal frequency swept over the passband or to a step-function. The swept frequency is time consuming and the step-function can produce a large overshoot in the tuning error. These test signals are also unsatisfactory for identification during normal synchrotron operation. Measuring during normal operation has the advantage that the loop can be made adaptive.

In the aerospace and process industries, Schroeder-phased harmonic signals[2] and Pseudo Random Binary Signals (PRBS)[3,4,5] are used for system identification. Of these, the PRBS were found to be the most suitable and easily adjustable for use under normal operation.

SCHROEDER-PHASED HARMONIC SIGNAL

The Schroeder-phased harmonic signal[2] is a composite of equally spaced phase modulated harmonics, with a given power spectrum:

$$y(t) = \sum_{k=1}^{N} \sqrt{p_k/2} \cdot \cos\left(\frac{2\pi kt}{T} + \phi_k\right) \quad (1)$$

* Operated by the Universities Research Associates, Inc, for the U.S. Department of Energy under Contract No. DE-AC02-89ER40486.

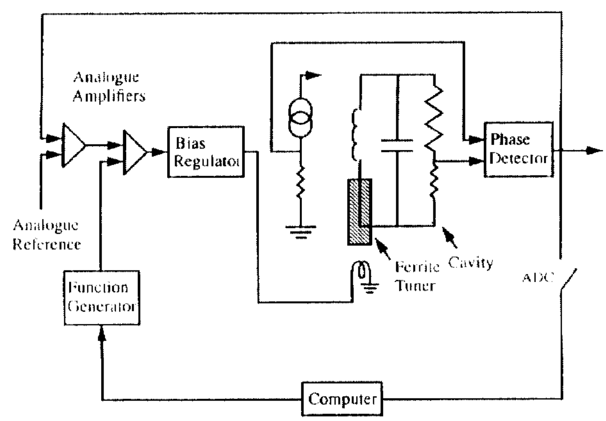

Figure 1: Block diagram of the augmented transfer function measurement scheme.

where, p_k is the relative power spectrum and ϕ_k the phase of the kth harmonic of the Fourier series of N harmonics with periodicity T. The phase modulation is given by:

$$\phi_k = \phi_1 - 2\pi \sum_{m=1}^{k-1} (k-m) p_m \quad (2)$$

where, ϕ_1 is the phase of the fundamental and p_m is the relative power spectrum of the mth harmonic.

The phase modulation results in a reduction in the peak value of the signal[2,3]. To obtain a flat output response requires a "prediction" of the input signal using the results of sinusoidal frequency sweep method. If $G(jw)$ is the response and $Y(jw)$ the Fourier transform from Eq. (1) then the required input spectrum $U(jw)$ is:

$$U(jw) = \frac{Y(jw)}{G(jw)} \quad (3)$$

where, $w = 2\pi k/N$ for harmonic k.

Figure 2 shows the response after several iterations of the input signal. Iterations are for a fixed power spectrum with phases modulated according to Eq. (2). This iterative process is a major disadvantage in the present application. The approach is useful when the input signal needs to have a band-limited power spectrum.

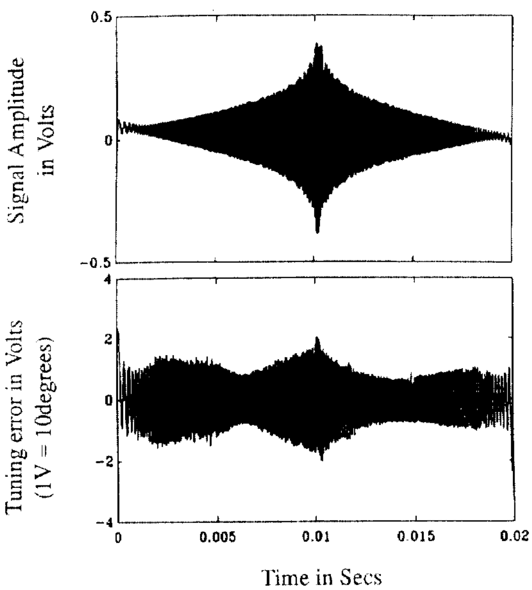

Figure 2: (a) Harmonic test signal shown for one full cycle. (b) Tuning error signal for excitation shown in Figure 2(a).

PSEUDO RANDOM BINARY SIGNAL

The advantage of random signals in system identification is their constant power spectrum and lack of periodic components in the signal. In addition their autocorrelation function is an impulse. In the absence of noise this can be arranged to be uncorrelated with any demand input signal present. This was not relevant to the present application. The autocorrelations for different signals are shown in Figure 3.

In practice it is easier to generate a pseudo random signal having some periodicity, but with an autocorrelation function closely approximating that of white noise. The binary form is more practical for system identification. Application of such a signal to the tuning loop is shown in Figure 4. Superimposed on the measured response is the calculated response from the model.

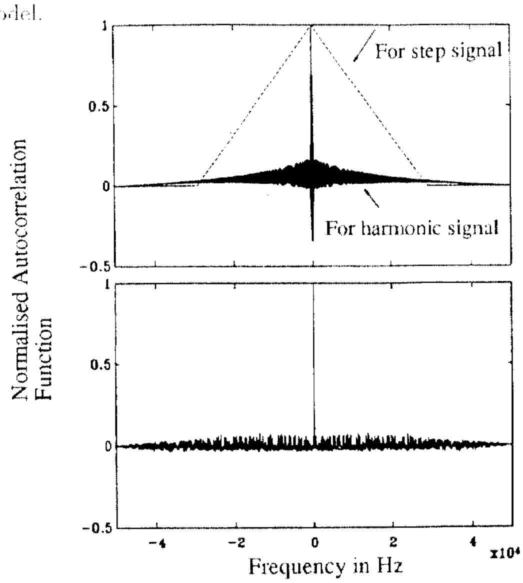

Figure 3: (a) Normalized autocorrelation function. (b) Normalized autocorrelation function of the PRBS signal.

Some care is required in generating the PRBS[3,4,5] to ensure it has the necessary autocorrelation function and power spectrum. The PRBS in Figure 4 was generated using the program of Ref. [3] and downloaded into the function generator in Figure 1.

A 4095 bit PRBS was generated with a 0.5 μs maximum pulse length. System identification is made in few synchrotron acceleration cycles. With no beam accelerated an amplitude of 0.15 V was used, but this was reduced to 75 mV when accelerating 1 E13 protons in 10 ms. At this level the PRBS perturbation resulted in a 10% beam loss. Limited resolution of the digital to analogue converter prevented further reduction of the PRBS.

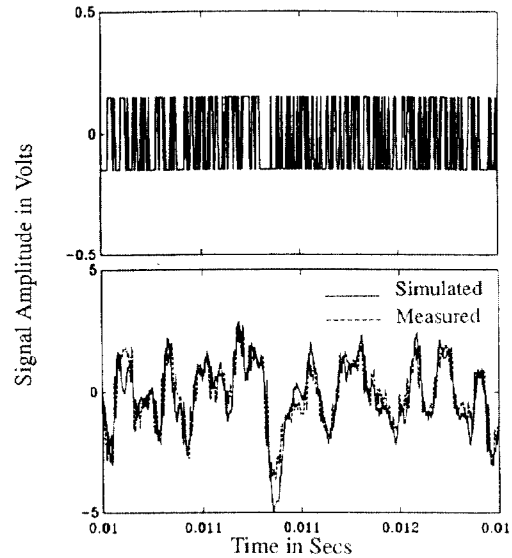

Figure 4: (a) PRBS test signal. (b) Simulated and measured tuning error signal.

FREQUENCY RESPONSE CHARACTERISTIC (NONPARAMETRIC)

The system characteristic in the frequency domain, $G(j\omega)$, is given by the ratio of the cross power, $\Phi_{uy}(j\omega)$, to auto power, $\Phi_{uu}(j\omega)$, spectral densities.

$$G(j\omega) = \frac{\Phi_{uy}(j\omega)}{\Phi_{uu}(j\omega)} . \quad (4)$$

Estimates of the cross and auto power spectral densities were made using the MATLAB[6] software. The transfer characteristic for all types of test signal are shown in Figure 5. Above 12 kHz the data is unreliable due to the tuning system band limitations. The PRBS results lie between those obtained with sinusoidal excitation obtained at max '*' and min 'o' gain points in the cycle. The different response to harmonic and step signals is probably due to poor spectral densities. The harmonic signal could be improved by redesigning its spectral density. For the step signal, overshoot drives the bias regulator into non-linear operation. The results approach the true response as the overshoot is reduced, but this is limited by measuring accuracy. Accuracy of estimation is judged by the coherence function, γ_{uy}:

$$\gamma_{uy} = \sqrt{\frac{|\Phi_{uy}|^2}{|\Phi_{uu}| \cdot |\Phi_{yy}|}} . \quad (5)$$

For a PRBS, a value of 0.8 is obtained over almost the full bandwidth, whereas step and harmonic signals show the presence of noise[3].

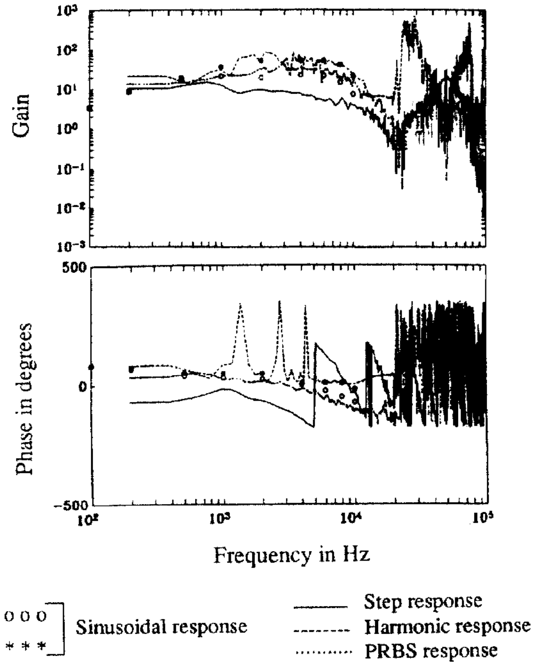

Figure 5: (a) Variation of gain values with respect to frequency. (b) Variation of phase values with respect to frequency.

TRANSFER FUNCTION MODEL (PARAMETRIC)

The z-transform of input-to-output is given by:

$$Y(z) = G(z)U(z) + H(z)E(z) \tag{6}$$

where, $Y(z)$ is the output signal, $U(z)$ the input containing the test signal and demand function, $E(z)$ the disturbance such as noise, $H(z)$ the transfer function for the disturbance and $G(z)$ is the system transfer function. Parameterizing the input-output data consists of curve fitting in the complex domain to a preconfigured model which can isolate the noise components $E(z)$, $H(z)$. The best model obtained for the PRBS input-output data is the "Output-Error" model[3,4]. The structure is given by:

$$U(z) = z^{-n_k}\frac{B(z)}{F(z)}U(z) + E(z) \tag{7}$$

with $B(z) = b_1 + b_2z^{-1} + b_3z^{-2} + \ldots + b_{n_b}z^{-(n_b-1)}$
$F(z) = 1 + a_1z^{-1} + a_2z^{-2} + \ldots + a_{n_a}z^{-n_a}$.

Calculation of the polynomial coefficients and their orders, n_a and n_b and the time delay n_k is done iteratively. The frequency characteristics of the 'optimised' model is shown in Figure 6 and provides a good description of the system over the 12 kHz bandwidth. The results are obtained using half the data the other half being retained for model validation tests. The validation results shown in Figure 4, use the same PRBS but measured at a different time. The pole-zero plot for the model is shown in Figure 7. The proximity of the poles to the unit circle shows the dynamic nature of the system.

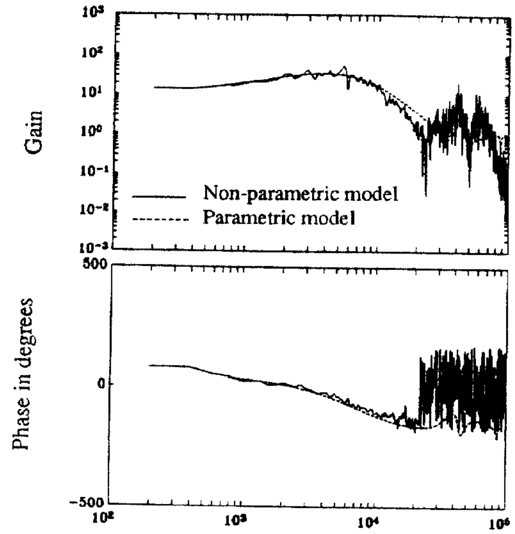

Figure 6: (a) Gain curves for parametric and nonparametric models. (b) Phase curves for parametric and nonparametric models.

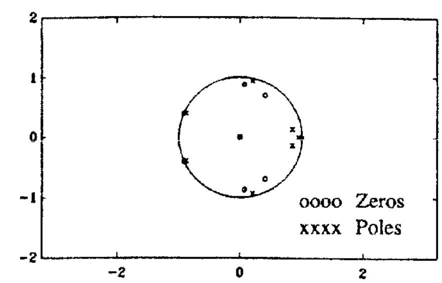

Figure 7: Location of poles and zeros on a unit circle.

CONCLUSION

The use of PRBS appears to provide a method of measuring transfer functions during normal synchrotron operation. This allows for the subsequent development of adaptive loops. The techniques can be extended to multi-input multi-output control systems provided uncorrelated test signals are used.[5]

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