"AN OVERVIEW OF FREQUENCY DOMAIN METHODOLOGY FOR SIMULATION SENSITIVITY ANALYSIS"

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ABSTRACT

In this paper, Frequency Domain Experiments (FDM) are reviewed for simulation sensitivity analysis. With very few runs of the model, this technique can be used to determine those factors which have the highest impact on model performance, to identify the form of an adequate meta-model for the simulation response, or to construct a path search algorithm for determining the optimal settings of model factors. Limited experience with the technique suggets that it is best suited for qualitative factor screening. Some technical requirements for the applicability of the technique along with some limitations are discussed. A comprehensive list of references is also presented.

I. INTRODUCTION

In a simulation study, it is necessary to choose values for the input variables of the model. These variables can be classified as factors or parameters. Factors are those variables which are under the control of the experimenter whereas parameters cannot be controlled. Determination of satisfactory (optimal ?) factor settings requires extensive experimentation with the simulation model. Parameters, on the other hand, are estimated through the analysis of real world data. Since both of these activities can be very expensive, simulation is still considered to be a decision tool of *"last resort."*

Recently, a new methodology was introduced to guide the experimenter in these tasks while significantly reducing the computational burden. *Frequency Domain Methodology* (FDM) represents a collection of procedures for simulation sensitivity analysis [Schruben and Cogliano, 1987]. The main objective of sensitivity analysis is to determine the impact of input variables on model behavior. Thus, sensitivity analysis may simply refer to the qualitative classification of input variables as being *significant* or *insignificant.* It may also refer to the construction of a response surface model for the simulation output as a function of the input variables. Finally, it may refer to the determination of optimal settings for input factors through response gradient estimation.

FDM can be useful in identifying those parameters that have the highest impact on system behavior so that data collection and analysis efforts can be concentrated on those particular parameters. It can also be useful in detecting "important" factors so that experimentation can focus on these factors to determine optimal settings. The reduction in computational effort is then realized by ignoring those variables that have no significant impact on system performance. In other words, using FDM as a preliminary step in system design reduces the factor space over which further experimentation has to be done. Moreover, elimination of unimportant parameters can result in reduced data collection costs.

FDM can also be useful in Response Surface Modeling (RSM) to identify the functional form of an adequate response surface. This is an important preliminary step in RSM since it is possible to effectively design an experiment to estimate the coefficients of the terms in the response surface *only after* its proper form is identified [Schruben and Cogliano, 1987].

Recently, FDM has also been used in devising algorithms for gradient estimation in the optimization of steady state simulation response [Jacobson, 1988]. The basic advantage of doing the optimization in the frequency domain as opposed to the time domain is the substantial savings in the number of runs one needs to make in order to obtain reliable gradient estimates.

This note provides an overview of the recent research in the Frequency Domain Methodology. It discusses the mechanics of FDM along with the related issues, criticisms, and further research questions.

II. FREQUENCY DOMAIN METHODOLOGY

A key assumption of FDM is that the model output can be represented as a polynomial function of the input variables. Such a function is called a *metamodel*. Metamodels are used for validation, estimation of factor interactions, control, and optimization [Kleijnen, 1987].

More specifically, if Y represents the simulation response of interest and x_1, x_2, .., x_p are the input variables, the expected response is characterized by:

$$E[Y] = \beta_0 + \sum_{i=1}^{q} \beta_i \tau_i \tag{1}$$

where $\beta_1,\ldots,\beta_q$ are real-valued coefficients and $\tau_1,\ldots,\tau_q$ are possible terms in the polynomial model; these terms are products of non-negative integer powers of the input variables. For example, τ_i may represent x_1^2 or x_1x_3.

In a FDM experiment, values for continuous variables are varied *during* the run according to sinusoidal oscillations at different frequencies. Qualitative or discrete variables can also be included through an oscillating randomization scheme over the set of possible values such as a coin flip with an oscillating probability of heads. The spectrum of the output process then reflects the relative strength of these oscillations, because, if the simulation response is sensitive to changes in one of the input variables, then oscillating that variable produces predictable oscillations in the output [Schruben and Cogliano, 1987]. The practice is analogous to a "black box" electrical system (e.g., an amplifier); the device has an input port for each input variable, and the oscillations are an application of power to this system [Sanchez and Schruben, 1986].

Most of the research effort in FDM has been in the domain of *factor screening*. In this qualitative setting, the main practical use of FDM is to guide the development of efficient conventional run-oriented experiments by screening out insignificant input variables and/or identifying interactions between these variables. Input variables that are found to be insignificant are then excluded from further experimentation; the designs for the conventional experiments are also chosen so that the estimators for coefficients of significant terms are not confounded.

In this setting, two runs of the simulation model are needed: a control run and a signal run. A *control run* is just a conventional simulation run where all input variables are kept constant at their nominal values. Its main purpose is to identify the natural cycles in the response. To this end, the power spectrum for the control run, called the *control spectrum*, is estimated. In the *signal run*, the values of input variables are varied according to sinusoidal oscillations. The frequency assigned to a particular input variable is called its *driving frequency*. Depending on the form of the relationship between a particular input variable and the model behavior, the effect of these oscillations appear at specific frequencies, called the *term indicator frequencies*, on the power spectrum of the signal run. The latter is called the *signal spectrum*. The relationships between the driving frequencies and the term indicator frequencies are described in detail in [Schruben and Cogliano, 1987]. The spectral *signal-to-noise ratio*, which is the ratio of the signal spectrum to the noise spectrum, is used in the analysis to eliminate the effect of any natural cycles. A high spectral-ratio value at an indicator frequency means that the impact of the associated term of input variables is significant.

Example: Suppose that the performance measure of interest of a system can be characterized as follows:

$$E[Y] = \beta_0+\beta_1X_1+\beta_2X_2+\beta_{11}X_1^2+\beta_{22}X_2^2+\beta_{12}X_1X_2 \qquad (2)$$

where β_j's are real-valued coefficients, and X_1 and X_2 are the input variables. To determine the relative significance of the terms, the FDM experiment is run in such a manner that, during the signal run, the values of the input variables are computed according to

$$X_1(t) = a + \alpha \cos(2\pi\omega_1 t)$$
$$X_2(t) = b + \alpha \cos(2\pi\omega_2 t)$$

where a and b are the nominal values of the input variables, α is the *oscillation amplitude*, ω_1 and ω_2 are the *driving frequencies* for the input variables, and t is an appropriate *driving index*. (The choice of a adequate driving index is discussed in [Jacobson et al., 1988]). Recall that, in the control run, the input variables are assigned their nominal values throughout the run. Then, the spectral-ratio values at the following indicator frequencies are observed to determine whether a particular term in (2) has a significant contribution to the measure of performance:

TERM	INDICATOR FREQUENCY
X_1	ω_1
X_2	ω_2
X_1^2	$2\omega_1$
X_2^2	$2\omega_2$
X_1X_2	$\omega_1+\omega_2$, $\omega_1-\omega_2$

The experimentation can then be continued by focusing only on those variables that have a significant impact on the outcome.

FDM is also useful for identifying the appropriate form of a response surface model for simulation output. Once the functional form of the response surface is identified, efficient experiments can be designed to estimate the coefficients of the involved terms. Schruben and Cogliano (1987) apply FDM to determine the form of the response surface by considering the class of all polynomial functions of order k (class of prospective response surface models) given by (1). The lack of fit by any polynomial of order less than equal to k is then indicated by significant output spectrum peaks at frequencies that are *not* indicator frequencies for terms in the class of prospective models. The quantification is made through a series of hypothesis tests where the null hypothesis is that term τ_j should not be included in the response surface model. In this setting, p+1 driving frequencies are selected to experiment with a model having p input variables. The actual experiment is run as a Latin square. Each driving frequency serves as a control frequency for one of the runs. This, in turn, provides a standard for comparing response spectrum peaks at that frequency. The mechanics of the procedure are discussed in detail in [Schruben and Cogliano, 1987] along with some examples. The limited experimentation shows that the polynomials identified by FDM are identical to those selected using conventional designs, which typically require a considerably higher number of runs. The relative efficiency of FDM with respect to the conventional methods increases with the number of input variables.

Jacobson (1988) uses the FDM approach to construct a path search optimization algorithm for simulation experiments. Through the *Hammerstein Model,* he characterizes the steady state simulation response with both memory and noise. He then devises a path search algorithm for a one-dimensional optimization problem using the output power spectrum. He develops estimators for gradient direction, Newton step size, and stopping criterion by extracting derivative information from the power spectrum of the simulation response. These estimators are shown to be asymptotically unbiased and consistent. Limited experimentation with queueing models provides encouraging results. Technical issues in simulation optimization are discussed in [Jacobson, 1989], [Jacobson et al, 1987], and [Jacobson et al, 1988].

Another advantage of FDM in comparison with other sensitivity analysis methods is that it does not require any additional effort for implementation. In other words, the simulation code need not be altered to run FDM experiments.

Detailed discussions can be found in [Schruben and Cogliano, 1987] about the implementation issues in FDM, in [Schruben, Heath and Buss, 1988] about the theoretical issues, and in [Morrice and Schruben, 1989] about the advantages and shortcomings of FDM with respect to some classical statistical procedures. A nontrivial application of FDM in factor screening is presented in [Sanchez and Schruben, 1986].

III. LIMITATIONS OF FDM

Critics of FDM focus mainly on two topics: *(i)* the use of spectral analysis, and *(ii)* the idea of changing values of variables *during* a run [Kleijnen, 1987]. Spectral analysis is a sophisticated technique. It also entails various technical questions such as the choice of "window" size, dependence among spectrum estimators, and choice of driving frequency values. The selection of a window type is usually dictated by the statistical properties such as consistency. The selection of a *truncation point*, m, on the other hand, involves a serious trade-off. A small value for m yields an estimator with low variance (high precision) whereas a large value of m yields a small bandwidth, b (high resolution). Recall that FDM requires spectral estimators that are at least one bandwidth apart for justifying the assumption of independence. On these technical issues, [Sanchez and Schruben, 1986] and [Schruben and Cogliano, 1987] recommend the use of *Tukey window* for its "desirable statistical properties such as consistency." They also recommend that the truncation point, m, should be chosen such that $m \geq 4/3b$. They further recommend, following Chatfield (1984), that the run length, n, should approximately be $(m/2)^2$. The point remains, however, that the selection of these parameters is largely an art form.

The second issue is mainly philosophical. Critics of this method claim that the practice violates the basic assumption of the original model that the parameters remain constant during the lifetime of the real system. They further claim that this approach simulates a different system than originally modeled [Kleijnen, 1987]. As Morrice and Schruben (1989) point out: "There is no question that a system will behave differently when its control knobs are twisted while the system is running; the practical issue is what information can be gained in this manner." The authors further emphasize that this practice takes advantage of one of the unique characteristics of computer simulation, namely *compressibility of time*. This is not available in most other statistical experiments (such as those in agriculture or medecine) where fixed-valued, parallel replications are the only option.

On the other hand, there are several theoretical requirements for FDM experiments. First, it is possible to define frequency spectra only for stationary stochastic processes. Hence, it may be difficult to justify the application of this methodology to terminating simulations and to simulations with an initial transient. Schruben and Cogliano (1987) report that, in practice, neither of these two situations pose a serious problem. In fact, most of their empirical work has been with terminating simulations. Also, they report that the initial transients in a simulation output appear in the frequency domain as "partially completed cycles at very low frequencies." These cycles can be viewed as naturally occurring low frequency components of a stationary stochastic process, which will be eliminated in the spectral ratio along with other natural cycles. Overall, a system must have the following charactersitics in order to apply FDM to identify a response surface model [Schruben and Cogliano, 1987]:

1. Parameter settings that can be changed during an experimental trial,

2. A response that can be observed at periodic intervals,

3. A response that can be modeled as a time-invariant linear combination of products of powers of the input variables.

Computer simulation programs make up an important special class of systems with the above characteristics. Hence, the FDM approach is applicable.

IV. FUTURE WORK

The limited experience with the Frequency Domain Methodology shows that the method is a promising tool for efficient sensitivity analysis. There are, however, various implementation issues that need to be addressed. These questions include serial dependence (gain) and noise in the output series, choice of a driving index, incorporation of variance reduction techniques, use of more general models for simulation optimization, and analysis of multi-variate simulation output.

An effective method of dealing with noise is presented in [Jacobson, 1989]; the problem of serial dependence (gain) is discussed in [Schruben and Cogliano, 1987]; indexing problem is addressed in [Jacobson et al, 1988]; generalization of models for simulation optimization and analysis of multi-variate output are mentioned in [Jacobson, 1988].

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