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The global simulation clock as the frequency domain experiment index

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ABSTRACT

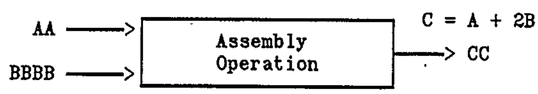
Frequency domain simulation experiments involve inducing sinusoidal variations in the input process. System sensitivities of the output can be detected in the frequency domain. The selection of an approprite index for these oscillations is critical in running such experiments. The index for the sinusoidal variations has typically been a discrete index such as customer or part number in queueing and production systems respectively. In this paper, the use of the global simulation clock as the index is discussed.

1. INTRODUCTION, BACKGROUND, AND MOTIVATION

Frequency Domain Methodology was first introduced by Schruben and Cogliano [5] as a means of identifying important factors in discrete event simulation responses. In recent years, much work has been done to develop the technique and extend its area of application (Jacobson, Buss and Schruben [1], Jacobson and Schruben [2], Morrice and Schruben [3], Sanchez and Buss [4], Schruben [6], Schruben, Heath and Buss [7], Som, Sargent and Schruben [8]).

When frequency domain simulation experiments are performed, an input process $x(t)$ is varied about $x(0)$ at driving frequency ω with oscillation amplitude α (i.e. $x(t)=x(0)+\alpha\sin(2\pi\omega t)$) where ω is in cycles per unit of t. The "time" index, t, may be the customer arrival number in queueing networks or job number in production, manufacturing, computing system and inventory models. In systems where customers or parts retain their identity, this index is sufficient; in fact, it is ideally suited to frequency domain experiments. However, if assemblies or separations occur, it may become unclear which index number to use at different points during the simulation run. A simple manufacturing example is the following:

Figure 1



Suppose the assembly station has average production rate μ and the average arrival rates for parts A and B are λ_A and λ_B, respectively. The inputs are varied according to

$$\begin{aligned} \lambda_A(t) &= \lambda_A(0) + \alpha_1\sin(2\pi\omega_1 t) \\ \lambda_B(t) &= \lambda_B(0) + \alpha_2\sin(2\pi\omega_2 t) \\ \mu(t) &= \mu(0) + \alpha_3\sin(2\pi\omega_3 t) \end{aligned} \tag{1}$$

In the assembly operation one part of type A is combined with two parts of type B, to form a new part of type C. There are four part numbers associated with this operation (one A, two B's, and one C). Which one should be used as the index in (1)? The difficulty of selecting an index from part numbers increases with the complexity of the manufacturing system which may involve shuffling of parts [8], multiple assembly operations, and / or discarding of parts.

It would be desireable to have a common index, t, for all parameters. An obvious choice is the global simulation clock. However, its application is not straightforward.

2. THE GLOBAL TIME CLOCK INDEX AND FREQUENCY SHIFTS

Consider using the global simulation clock as the oscillation index, t. In a frequency domain simulation experiment, the input process $x(t)$ can be described by $x(t)=x(0)+\alpha\sin(2\pi\omega t)$. When the oscillation index, t is customer number or part number, then $x(t)$ takes on values at $t=0,1,2,3,\ldots$. This results in an output value, $y(t)$, at

$t=0,1,2,3,\ldots$. Suppose we use the global simulation clock τ as the unit for t. Suppose further that the i^{th} customer or part is processed at time τ_i. This results in

$$x(\tau_0)=x(0)+\alpha\sin(2\pi\omega\tau_0)=x(0)$$
$$x(\tau_1)=x(0)+\alpha\sin(2\pi\omega\tau_1)$$
$$x(\tau_2)=x(0)+\alpha\sin(2\pi\omega\tau_2)$$
$$\vdots$$
$$x(\tau_n)=x(0)+\alpha\sin(2\pi\omega\tau_n).$$

where n is the number of customers or parts processed during the running of the simulation experiment. If the expected time between customers being processed at a particular server or machine is T time units, then we have $\omega\tau_i=T\omega(\tau_i/T)$. Since $E(\tau_i)=iT$, then $E(\omega\tau_i)=T\omega i$ for $i=1,2,\ldots,n$. Therefore using global simulation clock time as the index results in the frequencies with significant power spectrum values being rescaled by T, the expected time between customer or part service in the system. The value for T is typically known to the simulation user in simple models but may need to be estimated in more complex models. Since all the term indicator frequencies get rescaled by some T value associated with its corresponding server or machine input, the frequency selection problem discussed in [1] can be modified by using driving frequencies ω_k/T rather then the ω_k given in [1].

3. APPLICATIONS

This section will demonstrate and compare the effectiveness of the global simulation clock versus the customer or part number as the unit of index t. The comparison will be made using two simple examples.

EXAMPLE 1:

Consider the analysis of an M/M/1 queueing system using frequency domain methodology. A simulation model of the M/M/1 queue is run for n=50000 observations. The first 5000 observations are arbitrarily dropped to reduce the initial transient effect of the system. The output power spectrum is estimated with a Tukey lag window of $m=2\sqrt{(.9)n}=424$. The inputs μ and λ are varied according to the formulas $\mu(t)=\mu(0)+\alpha\sin(2\pi\omega_1 t)$ or $\lambda(t)=\lambda(0)+\alpha\sin(2\pi\omega_2 t)$ where $\mu(0)=1$ customers unit per of time and $\lambda(0)=.5$ customers per unit of time. The expected time between customers being served is $T=1/\lambda$ for systems with traffic intensity $\rho=\lambda/\mu<1$. Table 1 gives the values for ω_1, ω_2, α as well as the term indicator frequency for the linear term in the model.

Figures 2 and 3 depict the signal-to-noise ratio output power spectra for the case with $\mu(0)=1$, $\lambda(0)=.5$, and $\omega_1=.01$. Figures 4 and 5 depict the signal-to-noise ratio output power spectra for the case with $\mu(0)=1$, $\lambda(0)=.5$, $\omega_1=.005$, and $\omega_2=.02$. The expected time between customers being served is $T=1/\lambda(0)=2$. Therefore, the results given in Table 1 and depicted in Figures 2, 3, 4, and 5 demonstrate how the global simulation clock can be used to drive the input variations during a frequency domain experiment. In Table 1, the values of T are estimated from the signal run and results in a significant output power spectrum value at $\hat{T}\omega_1$ and/or $\hat{T}\omega_2$.

We should note that when we used the global simulation clock to drive the oscillations for both inputs λ and μ simultaneously, we found the system became more sensitive to oscillations into unstable regions (i.e. $\rho\geq1$). In fact, the output power spectra yielded false negatives if the oscillation amplitudes were chosen too large. This problem is discussed more fully in [3].

Table 1: Comparison of the Customer Number Versus Global Simulation Clock for an M/M/1 System

$\mu(0)$	$\lambda(0)$	ω_1	ω_2	α	$\hat{T}$	Linear Term Indicator Frequency (Time Clock)	(Customer Number)
1	.5	.01	0	.8	1.996	.02	.01
1	.8	.01	0	.6	1.248	.0125	.01
1	.5	0	.01	.4	2.053	.02	.01
1	.8	0	.01	.7	1.280	.0128	.01
1	.5	.005	.02	.25	2.020	(.01,.04)	(.005,.02)

EXAMPLE 2:

The simple assembly operation given in Figure 1 is simulated for a runsize of n = 50000 where the first 5000 observations are discarded to reduce initial transient effects of the system. The arrival and service distributions are assumed to be exponential with rates given in (1), where

$\lambda_A(0) = 0.5, \quad \lambda_B(0) = 1.0, \quad \mu(0) = 1.0,$
and $\alpha_1 = 0.3, \quad \alpha_2 = 0.6, \quad \alpha_3 = 0.6.$

The output time series is a record of the difference between each completion time of the assembly operation and the corresponding arrival time of the latest arriving component part. Any input parameter which influences this output will also influence the throughput of the system. The output power spectrum is estimated using Tukey lag window with m = 200.

Table 2 contains a summary of the simulation runs. As in example 1, the values for T are estimated in each signal run. Linear term indicator frequencies are provided for the global clock time index and the part number index for part type C. Note that the linear term indicator frequency for λ_B is twice the driving frequency, since two type B parts are contained in each type C part. Figure 6 is the signal-to-noise ratio when μ is varied and the part number index is used. Figure 7 contains the signal-to-noise ratio when μ is varied and global clock is used as the index. The results illustrate that the global clock time can be used successfully in this setting when one input parameter is varied during a run.

When more than one input parameter is varied during a run, the results for the global time clock index are not as good as the results for the part number index. Figure 8 is a signal-to-noise ratio when λ_A, λ_B, and μ are varied together and the part number in used as the index. It is clear that there is an important linear relationship between each input parameter and the output. When the global simulation clock is used as the index, the signal-to-noise ratio indicates that there is a linear relationship between each input parameter and the output, however, the results are not as clear as when the part number index is used (see Figure 9).

4. CONCLUSIONS

We have illustrated, using two simple simulation models, why the global clock is not necessarily a good index for running frequency domain experiments. However, this discussion has provided more insight into the indexing problem and, with subsequent work, may lead to a more general indexing scheme.

5. BIBLIOGRAPHY

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Table 2: Comparison of the Part Number versus Global Simulation Clock for an Assembly Operation

ω_1	ω_2	ω_3	T	Linear Term Indicator Frequency (Time Clock)	(Part No. for C)
.01	0	0	2.016	.02	.01
0	.01	0	0.996	.02	.02
0	0	.01	2.002	.02	.01
.03	.02	0	(2.096, 1.007)	(.06, .04)	(.03, .04)
.02	0	.03	(2.039, 2.039)	(.04, .06)	(.02, .03)
0	.01	.04	(0.999, 2.005)	(.02, .08)	(.01, .04)
.01	.03	.04	(2.005, 1.013, 2.026)	(.02,.06,.08)	(.01,.06,.04)

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Figure 2: Signal-to-noise ratio for an M/M/1 queue using customer number as the index of oscillation (n =45000, m=424).

```
  S   P   E   C  FREQ

0.45192852E+04   0.002  ***********
0.27384980E+04   0.005  ******
0.13016763E+04   0.007  ***
0.24714691E+05   0.010  *******************************************
0.13504166E+03   0.012  *
0.12929634E+03   0.015  *
0.10206436E+03   0.017  *
0.13484534E+04   0.020  ***
0.80758606E+02   0.022  *
0.55182663E+02   0.025  *
0.72187515E+02   0.027  *
0.28087549E+03   0.030  *
0.34028137E+02   0.032  *
0.31404129E+02   0.035  *
0.33247055E+02   0.037  *
0.72858276E+02   0.040  *
0.23109665E+02   0.042  *
0.26815445E+02   0.045  *
0.25419876E+02   0.047  *
0.24878372E+02   0.050  *
0.23567902E+02   0.052  *
0.19913940E+02   0.055  *
0.19512955E+02   0.057  *
0.24935593E+02   0.060  *
0.16865707E+02   0.063  *
0.16408279E+02   0.065  *
0.15299708E+02   0.067  *
0.16362961E+02   0.070  *
0.12282893E+02   0.072  *
0.16182877E+02   0.075  *
0.15024684E+02   0.077  *
0.12922046E+02   0.080  *
0.12324016E+02   0.082  *
0.12012040E+02   0.085  *
0.11048244E+02   0.087  *
0.10703652E+02   0.090  *
0.11434560E+02   0.092  *
0.10451986E+02   0.095  *
0.92460737E+01   0.097  *
0.94487228E+01   0.100  *
```

Figure 3: Signal-to-noise ratio for an M/M/1 queue using time as the index of oscillation (n=45000, m=424).

```
  S   P   E   C  FREQ

0.98002441E+02   0.002  ******
0.93909821E+02   0.005  *****
0.84279938E+02   0.007  *****
0.10609172E+03   0.010  ******
0.11619722E+03   0.012  *******
0.13964995E+03   0.015  ********
0.35993799E+03   0.017  *********************
0.94604517E+03   0.020  *****************************************
0.30174219E+03   0.022  *****************
0.93423249E+02   0.025  *****
0.61146439E+02   0.027  ****
0.53665039E+02   0.030  ***
0.44613083E+02   0.032  ***
0.55103683E+02   0.035  ***
0.71563934E+02   0.037  ****
0.65529007E+02   0.040  ****
0.56916656E+02   0.042  ****
0.42815048E+02   0.045  ***
0.30152679E+02   0.047  **
0.22397705E+02   0.050  **
0.22113388E+02   0.052  **
0.18938507E+02   0.055  **
0.17592987E+02   0.057  *
0.19970169E+02   0.060  **
0.14164737E+02   0.063  *
0.17341797E+02   0.065  *
0.12173473E+02   0.067  *
0.10414507E+02   0.070  *
0.10916085E+02   0.072  *
0.12811165E+02   0.075  *
0.97299728E+01   0.077  *
0.73708487E+01   0.080  *
0.78648453E+01   0.082  *
0.84696569E+01   0.085  *
0.72651529E+01   0.087  *
0.79402294E+01   0.090  *
0.68125763E+01   0.092  *
0.63888359E+01   0.095  *
0.58657417E+01   0.097  *
0.67445393E+01   0.100  *
```

Figure 4: Signal-to-noise ratio for an M/M/1 queue using customer number as the index of oscillation (n=45000, m=424).

```
  S   P   E   C  FREQ

0.70793953E+01   0.002  *********
0.43199585E+02   0.005  ****************************************
0.57621107E+01   0.007  *******
0.96676092E+01   0.010  ************
0.60184937E+01   0.012  *******
0.11478884E+02   0.015  **************
0.49799137E+01   0.017  ******
0.22938751E+02   0.020  ***************************
0.44208632E+01   0.022  ******
0.76089277E+01   0.025  *********
0.41877317E+01   0.027  *****
0.37517567E+01   0.030  *****
0.33193464E+01   0.032  ****
0.31423922E+01   0.035  ****
0.26137848E+01   0.037  ****
0.32884350E+01   0.040  ****
0.22340240E+01   0.042  ***
0.23616314E+01   0.045  ***
0.20602465E+01   0.047  ***
0.20019226E+01   0.050  ***
0.21418648E+01   0.052  ***
0.17830734E+01   0.055  ***
0.19292507E+01   0.057  ***
0.17168446E+01   0.060  **
0.15236053E+01   0.063  **
0.15246468E+01   0.065  **
0.14581470E+01   0.067  **
0.15298214E+01   0.070  **
0.15646057E+01   0.072  **
0.17883215E+01   0.075  ***
0.15507717E+01   0.077  **
0.14415722E+01   0.080  **
0.14034863E+01   0.082  **
0.14023581E+01   0.085  **
0.14823389E+01   0.087  **
0.15851450E+01   0.090  **
0.13925514E+01   0.092  **
0.12881737E+01   0.095  **
0.13974447E+01   0.097  **
0.14118128E+01   0.100  **
```

Figure 5: Signal-to-noise ratio for an M/M/1 queue using time as the index of oscillation (n=45000, m=424).

S P E C	FREQ	
0.90284004E+01	0.002	************
0.88654814E+01	0.005	************
0.99165344E+01	0.007	*************
0.39226013E+02	0.010	**
0.10164402E+02	0.012	*************
0.69185944E+01	0.015	*********
0.66831474E+01	0.017	*********
0.73035011E+01	0.020	**********
0.69318314E+01	0.022	*********
0.61472216E+01	0.025	********
0.71804943E+01	0.027	**********
0.68217392E+01	0.030	*********
0.54728575E+01	0.032	*******
0.53477440E+01	0.035	*******
0.51966772E+01	0.037	*******
0.55565805E+01	0.040	********
0.41740217E+01	0.042	******
0.36094990E+01	0.045	*****
0.35163956E+01	0.047	*****
0.29370289E+01	0.050	****
0.27767401E+01	0.052	****
0.24683704E+01	0.055	****
0.20466394E+01	0.057	***
0.23436222E+01	0.060	***
0.21908245E+01	0.063	***
0.22507324E+01	0.065	***
0.18158369E+01	0.067	***
0.17562943E+01	0.070	***
0.17703772E+01	0.072	***
0.20338774E+01	0.075	***
0.18648806E+01	0.077	***
0.16587477E+01	0.080	***
0.16144552E+01	0.082	***
0.16830807E+01	0.085	***
0.15561886E+01	0.087	**
0.15649452E+01	0.090	**
0.16740065E+01	0.092	***
0.14903479E+01	0.095	**
0.13358746E+01	0.097	**
0.13818665E+01	0.100	**

Figure 6: Signal-to-noise ratio for an assembly operation using part number as the index of oscillation (n=45000, m=200).

S P E C	FREQ	
0.37060669E+02	0.002	**********************
0.38565231E+02	0.005	***********************
0.63644547E+02	0.007	*************************************
0.90674149E+02	0.010	**
0.53335922E+02	0.012	*******************************
0.13546551E+02	0.015	********
0.14912633E+02	0.017	*********
0.17661697E+02	0.020	**********
0.11181921E+02	0.022	*******
0.44974089E+01	0.025	***
0.44850464E+01	0.027	***
0.46287327E+01	0.030	***
0.34821043E+01	0.032	**
0.30518923E+01	0.035	**
0.36624765E+01	0.037	***
0.34375973E+01	0.040	**
0.29221287E+01	0.042	**
0.29189463E+01	0.045	**
0.29515867E+01	0.047	**
0.27550354E+01	0.050	**
0.27023335E+01	0.052	**
0.26652260E+01	0.055	**
0.26744318E+01	0.057	**
0.28927774E+01	0.060	**
0.28516941E+01	0.063	**
0.25883980E+01	0.065	**
0.24690685E+01	0.067	**
0.25365648E+01	0.070	**
0.26706696E+01	0.072	**
0.24707108E+01	0.075	**
0.21055822E+01	0.077	**
0.20657549E+01	0.080	**
0.21768503E+01	0.082	**
0.22070732E+01	0.085	**
0.22304125E+01	0.087	**
0.22088442E+01	0.090	**
0.20002890E+01	0.092	**
0.19519844E+01	0.095	**
0.22216444E+01	0.097	**
0.23736382E+01	0.100	**

Figure 7: Signal-to-noise ratio for an assembly operation using time as the index of oscillation (n=45000, m=200).

S P E C	FREQ	
0.61711636E+01	0.002	*************
0.72917423E+01	0.005	****************
0.69182138E+01	0.007	***************
0.68971462E+01	0.010	***************
0.73934793E+01	0.012	****************
0.99998503E+01	0.015	*********************
0.19221771E+02	0.017	***
0.24230408E+02	0.020	**
0.15392470E+02	0.022	*********************************
0.62709141E+01	0.025	*************
0.40490799E+01	0.027	*********
0.32832298E+01	0.030	*******
0.30529175E+01	0.032	*******
0.38388500E+01	0.035	********
0.54869442E+01	0.037	************
0.51497478E+01	0.040	***********
0.40182467E+01	0.042	*********
0.36480827E+01	0.045	********
0.33234501E+01	0.047	*******
0.28212175E+01	0.050	******
0.26365967E+01	0.052	******
0.26906843E+01	0.055	******
0.26924238E+01	0.057	******
0.27079601E+01	0.060	******
0.25832348E+01	0.063	******
0.24081802E+01	0.065	*****
0.25394335E+01	0.067	******
0.26105604E+01	0.070	******
0.24488811E+01	0.072	******
0.21157084E+01	0.075	*****
0.17976665E+01	0.077	****
0.18606224E+01	0.080	****
0.21700792E+01	0.082	*****
0.22119141E+01	0.085	*****
0.20419989E+01	0.087	*****
0.19543991E+01	0.090	*****
0.19341822E+01	0.092	****
0.19675817E+01	0.095	*****
0.19391394E+01	0.097	*****
0.17877750E+01	0.100	****

Figure 8: Signal-to-noise ratio for an assembly operation using part number as the index of oscillation (n=45000, m=200).

S P E C	FREQ	
0.19565414E+02	0.002	******************************
0.16903137E+02	0.005	**************************
0.25528671E+02	0.007	**
0.29977615E+02	0.010	**
0.18210281E+02	0.012	****************************
0.89497404E+01	0.015	**************
0.99401360E+01	0.017	****************
0.11402999E+02	0.020	******************
0.92089977E+01	0.022	**************
0.62900782E+01	0.025	**********
0.65148325E+01	0.027	**********
0.77146387E+01	0.030	************
0.65476770E+01	0.032	**********
0.51994543E+01	0.035	********
0.19031052E+02	0.037	*****************************
0.32977753E+02	0.040	**
0.18691360E+02	0.042	*****************************
0.42147493E+01	0.045	*******
0.48645658E+01	0.047	********
0.52071390E+01	0.050	********
0.41101360E+01	0.052	*******
0.34763880E+01	0.055	******
0.58546734E+01	0.057	*********
0.80285807E+01	0.060	*************
0.52399788E+01	0.063	********
0.25396414E+01	0.065	****
0.24847422E+01	0.067	****
0.26258564E+01	0.070	****
0.24723244E+01	0.072	****
0.24957752E+01	0.075	****
0.39376736E+01	0.077	******
0.47903614E+01	0.080	********
0.33674126E+01	0.082	******
0.22169781E+01	0.085	****
0.23415298E+01	0.087	****
0.25133724E+01	0.090	****
0.23147049E+01	0.092	****
0.21562262E+01	0.095	****
0.26956997E+01	0.097	*****
0.32822065E+01	0.100	*****

Figure 9: Signal-to-noise ratio for an assembly operation using time as the index of oscillation (n=45000, m=200).

```
S   P   E   C  FREQ

.19901390E+01   0.002  ********************
.21526117E+01   0.005  **********************
.24602194E+01   0.007  *************************
.24729900E+01   0.010  *************************
.23159637E+01   0.012  ***********************
.24808693E+01   0.015  *************************
.37223444E+01   0.017  *************************************
.49901285E+01   0.020  **************************************************
.42719879E+01   0.022  *******************************************
.29218740E+01   0.025  *****************************
.26763506E+01   0.027  ***************************
.29221773E+01   0.030  *****************************
.26763744E+01   0.032  ***************************
.23818130E+01   0.035  ************************
.24741325E+01   0.037  *************************
.25995436E+01   0.040  **************************
.25998669E+01   0.042  **************************
.25735846E+01   0.045  **************************
.27473888E+01   0.047  ****************************
.29407120E+01   0.050  *****************************
.31086226E+01   0.052  *******************************
.33446808E+01   0.055  *********************************
.36519413E+01   0.057  *************************************
.38134193E+01   0.060  **************************************
.33725767E+01   0.063  **********************************
.29849606E+01   0.065  ******************************
.29920893E+01   0.067  ******************************
.32810936E+01   0.070  *********************************
.38640881E+01   0.072  ***************************************
.46024561E+01   0.075  **********************************************
.50482836E+01   0.077  **************************************************
.47595510E+01   0.080  ************************************************
.43621063E+01   0.082  ********************************************
.41148987E+01   0.085  *****************************************
.37802296E+01   0.087  **************************************
.31630592E+01   0.090  ********************************
.26316061E+01   0.092  **************************
.23931770E+01   0.095  ************************
.23432388E+01   0.097  ***********************
.23726358E+01   0.100  ************************
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