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Study of Uniform Experiment Design Method Applying to Civil Engineering

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Abstract

Uniform design (UD) method is one of the findings of number theory. UD has widely application scopes in traditional experimental design and compound design. Some newly developed applications by our team to civil engineering are introduced. These cases include experimental design of concrete corrosion by sulfuric acid, structural damage detection, calculation of response spectrum for stochastic pedestrian loads and reliability calculation of foundation pit and compartment fire. A nonparametric regression method, alternating conditional expectation (ACE), is also introduced to analyze the datum from UD in some cases. The results show that the UD is efficient and applicable in addressing many related problems in civil engineering since it can decrease the required number of experiments remarkably for both physical experiment and numerical experiment and cut down expense, calculation work and time. Therefore, the UD can be adopted to solve similar problems in the fields of civil engineering and other.

Keywords: uniform design; reliability; response surface; nonparametric regression

1. Introduction

Some problems in the field of civil engineering or other engineering are often involved a lot of physical tests, numerical calculations or simulation tests. For example, in material performance study, to obtain comprehensive information, reduce experimental errors and realize subsequent analysis, it is required

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setting the parameters into many levels in the range of experiment, which may cause many numbers of experiments. It leads to lots of cost as these experiments usually involve some expensive materials and equipment. Meanwhile, these experiments also need experimental stuff, so when number of experiments is lager, they may consume plenty of researchers' time. Although there is no need of economic cost for experiments involving numerical calculations or simulation, when the number of them is large, it also requires lots of analysis time.

Nomenclature

N	sampling number
P_f	failure probability
ε	fitting or calculation errors
q	level number of an experiment
s	parameter number of an experiment
η_f	combustion efficiency factor
γ_{qr}	smoke radiation coefficient
α_g	fire growth factor
$H_{c,net}$	net heat of combustion
$\dot{Q}_f$	characteristic hear release rate in unit area
q_f	fire load density
H_{fuel}	height of fire source

The Monte Carlo simulation (MCS) [1] and orthogonal experimental design (OD) [2] are often used to design and organize the foregoing experiments effectively. MCS has no need of specially designed input datum of experiment and it defines input datum by direct random sampling. However, its efficiency is low as it generally needs containing wide range of experimental datum and lots of experiments (simples). For example, a reliability analysis with failure probability P_f and relative error of simulation ε, the required sampling number of MCS N is

$$N \geq \left(\frac{100\varepsilon}{P_f} \right)^2 \tag{1}$$

Owing to failure probability Pf of a real structure is often in the range of 10-3~10-4, it can be deduced form the above Eq. (1) that MCS will lead to plenty of calculation effort. The OD uses some specially designed experiment tables to define input parameters. This method is wildly applied to experiment design in many domains. However, the number of OD is proportional to the square of the level number. When level number is large, the number of experiments will increase remarkably. So, if some method can decrease the required number of experiments without reducing the given precision, it will cut down expense and calculation work remarkably.

Actually, Fan and Wang [2,3] had studied similar questions in the 70s of the last century. Due to the need of designing missile, the original Seven Ministry of Machine proposed an experiment with 5 parameters and 31 levels for each parameter, and they required that the total number of experiments was no more than 50. For this experiment with 5 parameters and 31 levels, the number of comprehensive experiments is more than 2,800,000 and the number of experiments by OD is 961. It is clear that both of them exceed accepted number considerably. In order to solve this problem, Fan and Wang applied number theory into experiment design and created uniform experiment design method (UD). For the above problem, UD only needs 31 experiments and the results of which is approximate to those by 2,800,000 comprehensive experiments.

Similarly, for those problems involved repeated experiments and calculations in civil engineering can also consult UD to decrease required number of experiments, cost and calculation time. A brief description of UD is introduced and then some related researches [4,8] conducted by UD in our team are reviewed and at last, a case of using UD to deal with a reliability analysis is proposed to briefly explain the general procedure.

2. UD method

UD is based on uniform distribution in number theory. It makes experiment points uniformly scattered in the range of experiment parameters for getting more information by less experiments. Similar to OD, UD defines experiment points by some specially designed UD tables, the details of which can refer to *ref* [2]. But compare to OD, UD just takes uniform into consideration, so its points have better representative. And using UD, its number of experiments is proportional to the level numbers of parameters, while the number of OD is proportional to the square of level number. For an experiment with s parameters and q levels for each parameter, comprehensive experiment needs q^s experiments, OD generally needs q^2 and UD needs q experiments. It is clear that for experiments with many parameters and expensive cost, UD is a favourable and effective approach [3].

3. Using UD to organize numerical simulation experiments

Our team has adopted UD to solve the two following problems that require many numerical simulations: (1) damage identification of beam based on curvature mode [4]; (2) response spectrum of structure under random pedestrian loads [5, 6].

In structure non-destructive identification, the method based on curvature mode is wildly studied and applied for its simple operation and high sensibility [9-11]. Curvature mode can directly detect the damage location and show damage degree qualitatively, but quantitative identification of damage degree needs further research. Technically, damage degree can be detected simply by analyzing the variation of curvature mode of many structures with different damage location and degree. However, it will lead to plenty of calculation efforts. Therefore, UD is adopted in our team to define 30 representative structural samples with damage, and then equations of the relationship between the variation of curvature mode, damage position and damage degree was obtained by regression analysis on the input parameters defined by UD and variation values of curvature mode. The results of a few cases indicted that the equation had high precision and could detect single or multiple damage accurately, which proves that the calculation points determined by UD have high representativeness and the method can decrease total calculation effort remarkably [4].

Another problem is response spectrum of random pedestrian loads. With light weight and low damping ratio, some flexible structures are apt to be excited by pedestrian loads if they are not properly designed. This matter has attracted many researchers [12-16]. Essentially, pedestrian excitation is a narrow band random process, so it need considering probability to analyze structural random response under the random loads, i.e. a reliability problem with many uncertain parameters. Frequency domain analysis is usually used to solve this problem since this method is rapid and time-saving [17-19]. However, pedestrian excitation on the foregoing structures is transient and the frequency domain analysis cannot take this characteristic into account. Therefore, the MCS is usually adopted to simulate pedestrian loads to make further time-domain analysis. Therefore, UD was introduced to define some representative pedestrian loads and the acceleration response spectrum was obtained by dynamic analysis on the loads. After getting response surface between input parameters and the spectrum, the spectrum with a certain percentile was obtained by FOSM method. Comparing the results with the results of MCS, it is shown that this method only needs dozens of loads and can get results with high precision [5,6].

4. Using UD to organize physical experiment

In the field of civil engineering, many physical experiments are usually required to obtain quantitative relationship between parameters, e.g., studying parameters that could affect apparent diffusion coefficient D_{OH} in the mechanism of acid rain corroding concrete [20]. The D_{OH} has great influence on the corrosion and it is related to pH value of acid rain, water cement ratio of concrete and cement ratio. In order to obtain relationship between the three parameters and D_{OH}, a direct approach is to analyze D_{OH} under many different pH values, water cement ratios and cement ratios. Obviously, it will cause a lot of experiment work. Therefore, UD was introduced to reduce the required number of experiment and the cost of experiments in our team. And after obtaining experiment results, regression analysis between input parameters and output parameters is usually made to get explicit equation of the relationship. Parameter regression now is a widely used method. However, when involving many parameters, parameters that should be determined increase remarkably, which may lead to regression errors. Moreover, owing to the uncertainty of these objective principles, the parameter regression, which fits on the given function, also will cause error. Therefore, ACE (Alternating Conditional Expectations) regression method, a non-parameter regression, was introduced to obtain more appropriate regression in our research. Unlike parameter regression, there is no need of giving fitting function in ACE regression. It transforms original data and obtains an appropriate function with the best correlation according the characteristics of the input data and the output datum [21] which can improve correlation coefficient and regression effectiveness remarkably. Therefore, in our research, ACE regression method was adopted to make regression analysis for the data obtained by UD, and the quantitative relationship between the three parameters and D_{OH} is obtained, which can directly reflect influence of each parameter. The results show that applying UD and ACE regression to solve similar problems will obtain better effects.

5. Using UD and ACE to solve reliability problems

There are mainly two methods to calculate structure reliability [1]: moment method and MCS. The former one calculates each moment of limited state function (LSF), i.e., FOSM method. This method has high efficient and can obtain structure reliability relax by a few iterative calculations. But this method requires an explicit LSF since it requires obtaining direction cosine by calculate derivate of LSF. In fact, an explicit LSF is generally unknown in complex engineering. The MCS gets random samples of parameters by random sampling and then obtains structure failure probability by direct statistic analysis. Obviously, this method has no need of explicit LSF and can obtain failure probability with high precision just by enough simulations. This method, however, has plenty of calculation work, especially for each simulation that require much work, i.e. finite element analysis of fire structure dynamics or finite element analysis of foundation, it will cause considerable amounts of calculation work [7,8].

Response surface (RS) method is another wildly used approach to deal with engineering reliability. Considering that many reliability problems have no explicit LSF, RS method makes some experiments in an given range of parameters, and then based on experiments results, it obtains LSF by fitting analysis, i.e., linear or quadratic fitting. So the reliability index can be obtained by moment method according to the fitting LSF. The Experiment to define RS is an experiment involving *m* parameters and *n* levels. RS method based on UD was introduced to solve reliability of building fire and foundation engineering. The main calculation process was similar to RS method based on OD, but it adopted more efficient UD to organize experiment. As for constructing RS, ACE regression method was introduced to obtain a precise function between input and output datum.

6. An improved RS reliability case based on UD and ACE regression

To explain the main process of applying UD, a case of building fire reliability is introduced. Temperature and the thickness of smoke layer are the most important parameters to evaluate building fire risk. The main process using UD and ACE regression to find out the probability distributions of these two parameters is as follows.

6.1. Defining the parameter range and choosing appropriate UD table

The case suggested by Au [23] is adopted here. The analysis considers 7 random parameters: combustion efficiency factor η_f, smoke radiation coefficient γ_{qr}, fire growth factor α_g, net heat of combustion $H_{c,net}$, characteristic hear release rate in unit area $\dot{Q}_f$, fire load density q_f, and height of fire source H_{fuel}. These 7 parameters are normal and experiment range of each parameter is *mean* $\pm$ *standard deviation*. Choosing UD table $U_{24}^*(24^7)$, each parameter is equally divided into 24 levels in the range. According to the table and levels, parameters of each experiment are defined.

6.2. Fire dynamic calculation and RS analysis

The temperature and the thickness of smoke layer of each experiment defined by UD can be obtained by CFAST software. The regression analysis of RS between input parameters and output parameters can be done according to the results. As for RS regression, ACE regression is adopted. The analysis processes is shown in some related references [7,8]. The fitting correlation coefficient of temperature and thickness of smoke layer are 0.9972 and 0.9988 respectively, which show that the method has good fitting results.

6.3. Reliability calculation

Once obtaining the foregoing RS, the reliability index and the CDF of temperature and thickness of smoke layer can be deduced from FOSM method. The results of this method are shown in Fig.1 and 2 as RS+FOSM. It is noted that the correlation coefficient of RS regressed by ACE method are very close to 1, so the probability distribution can be obtained directly by MCS based on RS (RS+MCS). The probability distribution of smoke layer and temperature obtained by 5000 RS+MCS and the DMCS based on CFAST (DMCS+CFAST) are shown in Fig. 1 and 2 respectively. As can be seen, their differences are small, but the computation effort of the three approaches above depends on the times of repeatedly calling CFAST. The former two methods invoke only 24 CFAST callings, while the last method executes 5000 callings. Obviously, computation efficiencies of the two approaches based on improved RS are high.

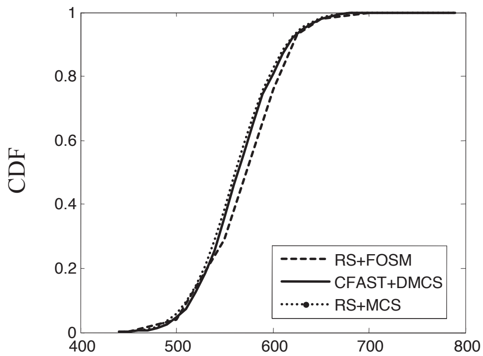

Fig.1 The CDF of maximum smoke temperature.

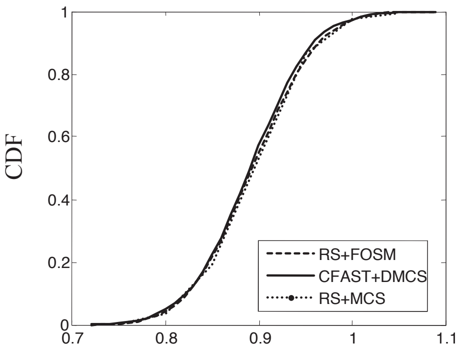

Fig.2 The CDF of maximum depth of smoke layer.

7. Conclusions

Some researches of applying UD to civil engineering are reviewed and a case is introduced to show the calculation process. It can be seen that UD can both decrease required number of experiments remarkably and solve these problems efficiently. From the foregoing problems that are solved successfully, it is shown that the UD, especially combining with ACE regression, is feasible and applicable in addressing many related problems in civil engineering. It can decrease the number of experiments remarkably for both physical experiment and numerical experiment, which can cut down the expense costs, calculation work and calculation time. Therefore, the UD can be adopted to solve similar problems in the fields of civil engineering and other.

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