Collection de notes internes
de la Direction
des Etudes et Recherches

Production d'énergie (hydraulique, thermique et nucléaire)

MODELE AUX ELEMENTS FINIS D'UNE GRAPPE DE COMMANDE. ETUDE PARAMETRIQUE MENEE PAR LA METHODE DES PLANS D'EXPERIENCE

FEM OF PWR'S CONTROL ROD CLUSTER, PARAMETRICAL STUDY BY EXPERIMENT DESIGN METHOD

97NB(0092

EDF
Electricité de France

DIRECTION DES ÉTUDES ET RECHERCHES
SERVICE ENSEMBLES DE PRODUCTION
DÉPARTEMENT ACOUSTIQUE ET MÉCANIQUE VIBRATOIRE

EDF
Electricité de France

Mars 1997

BOSSELUT D.
REGNIER G.
SOULIER B.

MODELE AUX ELEMENTS FINIS D'UNE GRAPPE DE COMMANDE. ETUDE PARAMETRIQUE MENEE PAR LA METHODE DES PLANS D'EXPERIENCE

FEM OF PWR'S CONTROL ROD CLUSTER, PARAMETRICAL STUDY BY EXPERIMENT DESIGN METHOD

Pages : 12

97NB00092

Diffusion : J.-M. Lecœuvre
EDF-DER
Service IPN. Département PROVAL
1, avenue du Général-de-Gaulle
92141 Clamart Cedex

ISSN 1161-0611

SYNTHÈSE :

Ce rapport présente une étude paramétrique sur le comportement vibratoire non-linéaire des grappes de commande des réacteurs à eau pressurisée.

Dans une première partie, le modèle Eléments Finis et les excitations prises en compte sont présentés. Les grandeurs de sortie du calcul sont les déplacements des crayons dans leur guidage, les forces de choc contre le guidage et la puissance d'usure développée.

Dans une deuxième partie, l'étendue de l'étude paramétrique est détaillée. La méthode des Plans d'Expérience utilisée tente d'approcher une surface de réponse par un polynôme. La construction du plan d'expérience est brossée en regard des contraintes imposées sur les paramètres. Dans cette approche globale, le modèle retenu de degré est composé pour chacun des 6 paramètres de tous les termes linéaires, quadratiques et d'interaction (26 coefficients). L'étude des forces RMS de choc et des puissances d'usure sur chacun des 17 points de guidage du crayon conduit à 34 polynômes.

Dans la troisième partie, un tableau d'analyse des résultats (orientée plus spécialement sur les puissances d'usure), met en évidence les paramètres importants à chaque point du guidage et leur distribution le long du crayon. L'étude des surfaces de réponses des paramètres deux à deux, permet de visualiser les interactions.

L'intérêt de la méthode des Plans d'Expérience est soulignée. Sa rigueur et son systématisme permettent au spécialiste de déceler les paramètres influents. La simulation simplifiée par de simples polynômes est moins coûteuse en temps de calcul. Là l'ensemble des solutions permet de comparer les résultats au retour d'expérience.

EXECUTIVE SUMMARY :

of

Some finite element models have been performed at EDF to simulate the vibrations of rod cluster and to analyse the wear phenomenon of rods using parametrical studies. In the first part, one the finite element models is presented. The location of excitation sources is described. The calculated values are : rod displacement in the guiding cards, shock forces on the guiding cards and wear power produced.

In the second part, a parametrical study is presented for a given computer experiment domain with an Experimental Design method. The building of the computer experiment design is described. The used polynomial model has all linear, quadratic and interactive terms for each of the 6 parameters (26 coefficients), 34 polynomials have been built to approach the effective shock forces and the mean wear power at each of the 17 guiding points.

In the last part, the influence of parameters on calculated mean wear power is shown along rods and some responses surfaces are visualized.

Systematism and closeness of experiment design technique is underlined. Easy simulation of all the response domain by polynomial approach, allows comparison with experiment feedback.

~~FINITE ELEMENT~~

PWR TYPE REACTORS

FINITE ELEMENT METHOD

CONTROL ELEMENTS

MECHANICAL VIBRATIONS

WEAR

PARAMETRIC ANALYSIS

~~DESIGN~~

E3200

F.E.M. of PWR's control rod cluster.
Parametrical study of vibrating behavior
by an Experiment Design method.

Didier BOSSELUT
EDF-DER-AMV 1 av du Gal de Gaulle 91141 CLAMART
Gilles REGNIER
ENSAM-LTVP 151 bd de l'Hôpital 75013 PARIS
Bruno SOULIER
DER mécanique Pôle universitaire Léonard de Vinci 92916 PARIS - la Défense

INTRODUCTION

Many damaging processes have to be taken into account to keep Pressurized Water Reactor (PWR) components in highly reliable operating conditions for more than forty years.
For example, systematic examinations on control rod cluster by ultrasonic method during maintenance shutdown show wear scars on stop clusters. These clusters always remain in the same "up" position. Their only goal is to quickly stop the nuclear reaction by falling down. The wear damage observed is sometimes strong enough to reject some of these clusters.
Rod cluster wear is due to impact-friction vibrations on loose support of guide tube. These vibrations are generated by primary coolant fluid circulation. The understanding of these problems is important because of reactor safety and replacement cost. It has motivated a great research and development program at EDF.
Finite element models (F.E.M.) developed using EDF mechanical computer code (*Code_Aster*) allow to simulate the non-linear behavior of this component.

1. MODEL DESCRIPTION

The mechanical model is a stick model without fluid meshing [1]. It is composed of a drive rod, a spider and a simplified cluster with only two rods instead of 24: one real rod (with realistic technical description) and an equivalent rod representing the 23 others (mass and stiffness calculated to keep an equal modal response). For both of them, lateral displacements are limited by 17 shock points (physical non-linearities) which simulate the three parts of the tube guide (discontinuous, continuous and fuel guides, fig. 1).

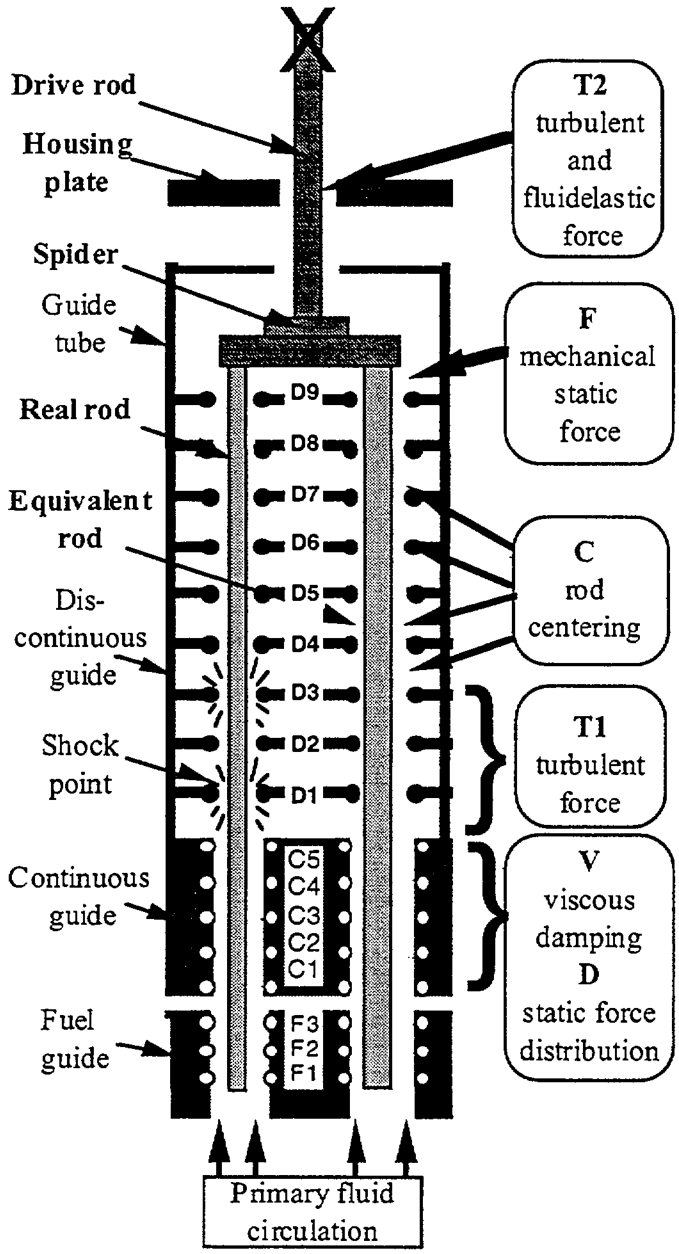


Fig. 1 - Description of the control rod cluster model

Excitation sources for this component have mainly hydraulic origins. All hydraulic forces introduced in the model have been studied on several hydraulic testing benches.

The most important one is Turbulent (T1) and located on the lower part of the rods between C5 and D3 cards.

The second one (T2) is both Turbulent and fluidelastic. It is due to the fluid circulation between the housing plate and the drive rod.

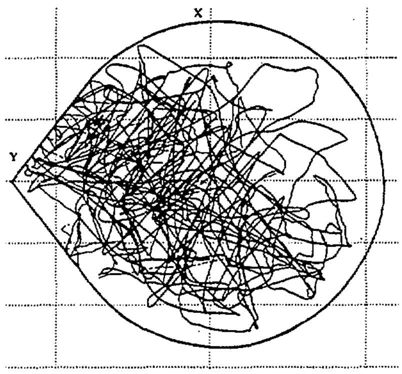
The profile of the static force Distribution (D) in the continuous guide depends on rod family in the cluster.

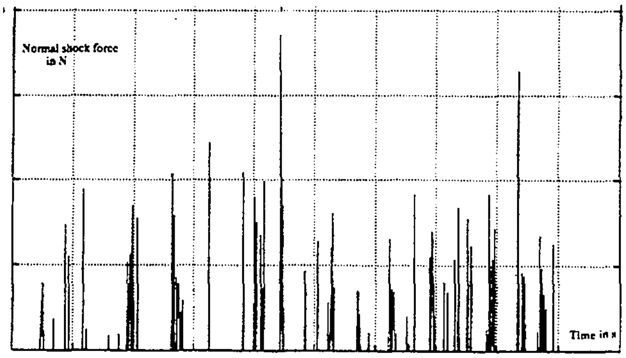
A light Viscous damping (V) appears in the continuous guide (rods are highly confined).

Mechanical or hydraulic static Forces (F) may occur on upper cards of the discontinuous guide (on D9 in this study).

Moreover, a rod static discentering is possible in its loose support.

A calculation needs 700 s CPU on CRAY C98 because of the physical non linearities number. It gives two time-dependent outputs for each guiding cards (Fi, Ci, Di): rod displacements and rod shock forces on the guide (fig. 2). A statistical treatment is made on these quantities. Wear power is the product of normal shock force and tangential speed.





XY Rod displacements in a guiding card — Shock forces against a guiding card

Fig. 2 - Example of the Finite Element Model outputs on D1 non-linearity

2. PARAMETRICAL STUDY

To analyse the mechanical behavior of the model and to understand the wear phenomenon, several parametrical studies have been performed. In the wide study presented here, the computational experiments have been defined by the variations of six parameters. The minimum and maximum levels of parameters which define the computational domain are given in table 1.

Parameter	D	F	T2	T1	V	C
Parameter type	qualitative criterion	force en D9	adimensional coefficient	adimensional coefficient	viscous damping	Y centering D9 to D1
Utmost values	A,B,E type of force distribution	O to 6 (N)	1 to 3 times a known solicitation	0 to 0.25 times a known solicitation	0 to 30 (Ns/m)	-0.5 to 0.5 (mm)

Table 1 - Computer experiment domain

To know parameter contributions on the chosen responses for this study (effective normal force and mean wear power), and to have quickly a good view of the global response surfaces in the experimental domain, a numerical Experiment Design (E.D.) [2] [3] has been carried out.

2.1 Experiment design principle

Response surfaces [4] can be approximated by a polynomial model: by example the mean wear power for the card D1 with 4 parameters (1). This type of approximation is valid if the response surfaces are smooth enough, without discontinuities. We assume it is the case for the two responses in this study: effective normal force and mean wear power. Variables in this model which represent the parameter variations and the interactions between parameters (linear and quadratic) are adimensioned (they vary between -1 and 1).

$$Pw_{D1} = 2.1 - 0.4D - 0.1F - 0.13T_2 + 3.7T_1 + 0.25D^2 - 0.05F^2 + 0.17T_2^2 + 0.2T_1^2 2 \\ +2.2DT_2 + 0.14DF - 0.06FT_2 - 0.63FT_1 + 0.41FT_1 + 0.58T_1T_2 \quad (1)$$

The coefficients of the polynomial model are identified by linear regression from a set of calculations (equation 3). For an N-calculation sample, the experiment problem is written in the following matricial form :

$$Y = X.A + E \quad (2)$$

where Y is the vector of the N calculated responses, A is the vector of k+1 coefficients to be estimated, X is a matrix of k+1 columns and N rows (constituted of 1 and k parameter values set for each calculation), and E denotes the modelling errors, called residuals (differences between the finite element model and the polynomial one). The coefficient vector A is estimated by a minimisation of the square residual sum :

$$\hat{A} = (X'X)^{-1} X'Y \qquad \text{where } X' \text{ denotes } X \text{ transpose.} \quad (3)$$

Assuming that the residuals can be represented by a Gaussian law with a constant variance σ^2 in the computer experiment domain (hypothesis which can be a posteriori verified), the covariance matrix only depends on the choice of calculation points:

$$\text{cov}(\hat{A}) = (X'X)^{-1}.\sigma^2 \quad (4)$$

The diagonal terms represent the variance of coefficients and the cross-coupling terms the correlations between coefficients. Precision and correlation between parameters do not depend on responses, so it is possible to define a priori a set of adequate calculations by minimising the terms of the covariance matrix. This is the basis of experiment design building.

2.2 Building of the calculation design

Several predefined experiment designs [4][5] have been defined and optimised to study response surfaces. One of the most well known designs is the composite design.
To have the opportunity of easily adding parameters in the study, a Doehlert design [6] has been chosen.

Predefined experiment designs can be modified to integrate constraints by building D-optimal designs [7]. To take into account the qualitative parameter D with three levels, the Doehlert design has been modified: a five-level parameter has been changed into a three-level parameter. Two experiments in the original design (4 parameters - 21 experiments - table 2) were suppressed.

Experiment number	D	F	T2	T1
1	0	0	0	0
2	1	0	0	0
3	-1	0	0	0
4	0.5	0.866	0	0
5	-0.5	-0.866	0	0
6	0.5	-0.866	0	0
7	-0.5	0.866	0	0
8	0.5	0.289	0.816	0
9	-0.5	-0.289	-0.816	0
10	0.5	-0.289	-0.816	0
11	0	0.577	-0.816	0
12	-0.5	0.289	0.816	0
13	0	-0.577	0.816	0

Experiment number	D	F	T2	T1
14	0.5	0.289	0.204	0.791
15	-0.5	-0.289	-0.204	-0.791
16	0..5	-0.289	-0.204	-0.791
17	0	0.577	-0.204	-0.791
18	0	0	0.612	-0.791
19	-0.5	0.289	0.204	0.791
20	0	-0.577	0.204	0.791
21	0	0	-0.612	0.791
a	-0.5	-0.866	-0.816	0.791
b	0.5	0.866	-0.816	0.791
c	0.5	-0.866	0.816	0.791
d	0	0.866	0.816	0.791

Suppressed experiments (experiments 2 and 3)   Added experiments (experiments a, b, c, d)

Table 2 - Modified Doehlert design for four parameters (normalised parameters)

Four experiments were added to significantly decrease the correlations between parameters by maximising the determinant of the covariance matrix. NEMROD software [8] which is based on a Fedorov algorithm [9] has been used.

Several criteria can be used to estimate the quality of the experiment design [3][5]; for example the trace of X'X, which is proportional to the sum of the coefficient variances, has been divided by more than two by adding 4 adequate experiments to Doehlert design (table2).

The parametrical study has begun with four parameters (23 calculations) and then 22 calculations have been added to analyse two other parameter influences. Complete study with 6 parameters would need 21609 F.E.M. calculations.

3. ANALYSIS AND RESULTS

3.1 Domain of validity

Conclusions of such a study must be strictly limited to the computational experiment domain. As a consequence, extrapolations of polynomial model do not have any sense. Parameters effects are just valid in their variation range and a non significant parameter in the variation domain may become important with a wider range. In this paper, the validity of F.E.M. model is not discussed.

3.2 Results presentation

The amount of results is important: two responses (effective normal shock force and mean wear power) at each of the 17 guiding points means 34 polynomials to analyse. In the case of 6 parameters, each polynomial has 26 coefficients and a constant term. Coefficients analysis allows hierarchization of parameters. Table 3 presents polynomials coefficients obtained for mean wear power at the 17 guiding points.

	Linear terms						Quadratic terms				Interaction terms					
Card	D	F	T_2	T_1	V	C	D^2	F^2	T_1^2	C^2	DT_1	FT_1	T_2V	T_1V	FC	T_1C
D9		1.2		1.9		7.2				11.1					6.7	6.7
D8		0.9		0.6		0.4		0.5		-0.3		0.7			0.6	
D7		0.2		0.7		0.3		-0.3		-0.3			-0.6			0.5
D6				0.5		0.3		0.2	0.2	0.3			-0.5			0.6
D5				0.6		0.1			0.3	0.2			-0.8			
D4				0.8	0.2	0.2			0.6				-1.4			
D3			-0.1	0.7	0.2	0.2			0.5	0.3			-1.1			
D2	0.1	-0.1		0.3		0.1			0.1	0.2						
D1	-0.5		-0.4	4.1		1.1			1.7	2.3			-3.4		2.1	1.9
C5				0.7	-0.3	0.2				0.9				-0.8	0.9	
C4	-1.3						1.6								-1.6	
C3	-0.7						0.8		0.4		-0.2					
C2	-0.5						0.6		0.3		-0.2					
C1				0.5	-0.2		-0.6									
F3	0.6			0.7			1.4		0.8		1.0					
F2	0.2			0.1			0.2				0.3					
F1	0.2			0.7	-0.2		-0.4				0.4		-0.6			

x	Highly significant parameter	Non significant columns are suppressed
x	Significant parameter	
	Less significant parameter	

Table 3 - Polynomial coefficients for mean wear power on guiding points.

Numbers indicated in each cell of the table 3 are the estimated polynomial coefficients. They represent the physical values of linear, quadratic or interactive effect of parameters.

For wear power at D1 card. complete polynomial form may be reduced to equation (5) which has only 10 terms:

$$Pw_{D1} = 2.3 - 0.5D - 0,4T_2 + 4,1T_1 + 1,1C + 1,7T_1^2 + 2,3C^2 - 3,4T_2V + 2,1FC + 1,9T_1C \quad (5)$$

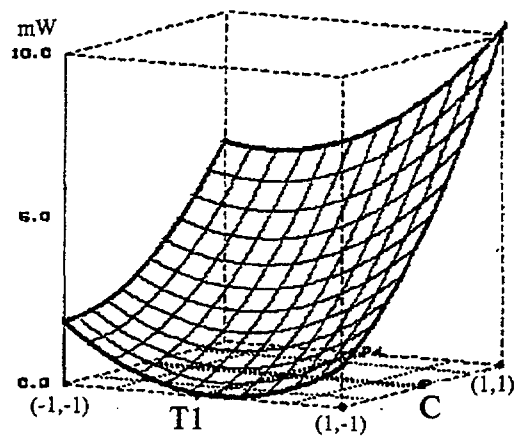
To evaluate if a coefficient is significant, its value is compared to the mean residual deviation between F.E.M. and polynomial calculations. Of course, this evaluation depends on the quality of regression analysis. It indicates the capability of the polynomial model to approach the surface response.

3.3 -Results analysis

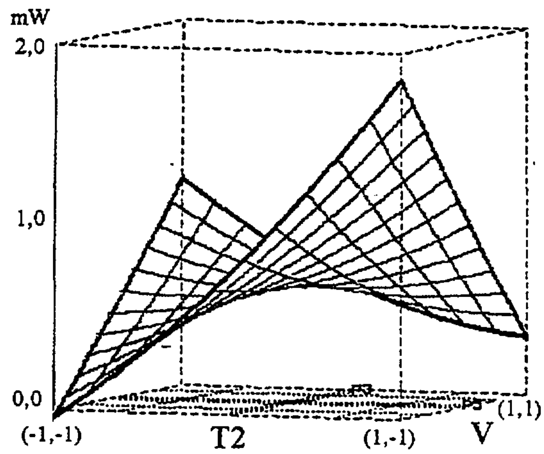
A global analysis of parameters effects is possible using table 3. It shows the most important parameters and locates their effect along the cluster. Linear terms are the most significant (more than a half of highly significant terms). But the highest value is a quadratic effect of discentering. Global effect of one parameter is obtained by looking all linear, quadratic and interactive terms where it appears:

- static force distribution D has an effect located in continuous guide where it is applied and in fuel guide. It has no effect elsewhere.
- static force F applied at D9, has an effect from D9 to D6.
- excitation T2 has no large effect in this variation range excepted interaction with viscous damping from D1 to D7.
- excitation T1 is very important everywhere excepted in the continuous guide.
- viscous damping V has a light effect in the terminal low part and an interaction with T2 above the continuous guide.
- centering C is significant and important, particularly at D9. It interacts with F and T1.

It is also possible to plot response location surface of parameters by couple, the others being fixed at middle point. Figure 3a illustrates light interaction between excitation T1 and centering C on card D1 and Figure 3b strong interaction between excitation T2 and viscous damping V on card D3.



3a -Interaction of T1 and C on D1 card

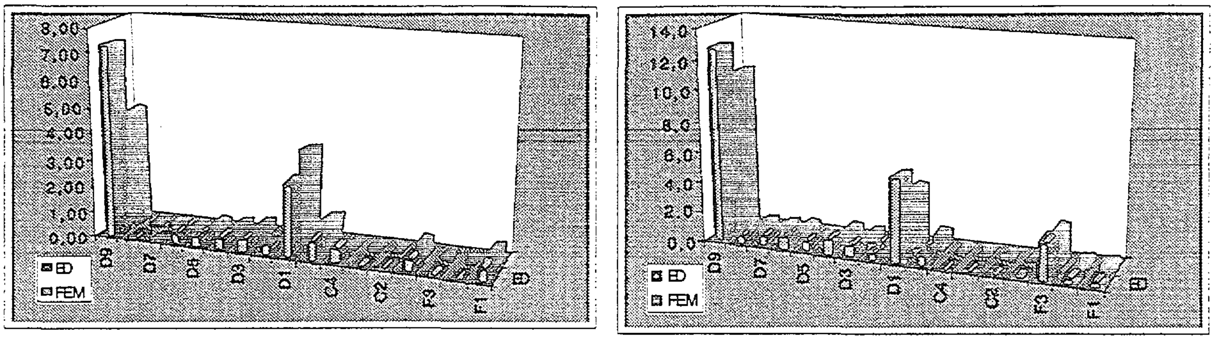


3b - Interaction of T2 and V on D3 card

Fig. 3 - Response surface of parameters by couple

Mean residuals observation allows to say that polynomial approach is well adapted. On 16 of the 17 guiding points, less than 5% of response variations stay not fully explained by polynomial models. On D9, wear response is perhaps too non-linear for E.D. method.

Figure 4 shows comparison between E.D. expectation and F.E.M. calculation (done a posteriori) for two random examples out of prime design.
Some differences appear but globally the distribution along the cluster is well estimated. Nevertheless, these differences are included in the confidence interval defined by the mean residual deviation between F.E.M. and E.D. calculations.



Experiment n° 516 Experiment n° 3465

Fig. 4 - Comparison between E.D. expectation and F.E.M. calculation along the cluster

For an example of estimation quality, the local effect on F3 observed in F.E.M. experiment n° 3465 (figure 4) is well simulated by E.D. calculations.

CONCLUSION

This original use of Experiment Design method for numerical model analysis allows to perform computer experiments in a rational way with a minimum number of calculations; the benefit becomes greater as the number of parameters increases. Display of response surfaces and determination of parameter contribution to response (here effective normal force and mean wear power) can help specialists to have a global vision on simulated physical phenomenon in a defined experiment domain. This global vision is important to point out influent parameters and to compare numerical results to feedback.

REFERENCES

1. Jacquart G.. Bosselut D. 1993, Impact friction vibrations on tubular structures: numerical simulation and experimental validation. *EDF Mechanical Seminary*. Beaune. France.

2. Morris M.D. 1991. Factorial sampling plans for preliminary computational experiments. *Technometrics*. Vol. 33. No 2. 161-174.

3. Sachs J.. Welch W.J.. Mitchell T.J.. Wynn H.P. 1989. Design and analysis of computer experiments. *Statistical Science*. Vol 4. No 4. 409-435.

4. Box G.E.P.. Draper N.R.. 1987. *Empirical model-building and surface response*. Wiley InterScience. New York.

5. Benoist D.. Tourbier Y.. Germain-Tourbier S. 1994. *Plans d'expériences : construction et analyse*. Technique et Documentation - Lavoisier. Paris.

6. Doehlert D.H. 1970. Uniform Shell Designs. Applied Statistics. Vol 19. 231-239

7. Régnier G.. Soulier B. 1993. Experimental designs for an experimental modelling of material or structural tests. *Probabilities and Materials*. 197-298

8. Mathieu D.. Phan-Tan-Luu R. 1986. *NEMROD software V3.0*. LPRAI. Marseille University

9. Fedorov V.V. 1972. Theory of optimal experiments. Academic Press. London.