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SOFTWARE SUPPORT FOR IDENTIFICATION OF STOCHASTICALLY LOADED PARTS OF MECHANICAL CONSTRUCTIONS

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***Abstract**: In article is described possible way of identification of stochastically loaded mechanical constructions of machines for purpose of predictive controlling their activity in real loading conditions. Concretely it concerns project of application of vector autoregressive (ARMAV) models, which parameters are possible to identify through application of vector modification of nonlinear least squares method. Article includes theoretic base of solved problems, description of realisation of method testing process and brief interpretation of verification results of functionality processed software and accuracy realized computations.*
***Key words:** Mechanical Structures, Stochastic Load, Vector Autoregressive Models, Software Support for Identification - ArmaGet, Verification of Results of Identification.*

INTRODUCTION

In spite of maximal effort of constructors is not possible to ensure complete readiness of constructions of various machines and appliances for all possible operational situations and conditions. It is evident, that running of most of machines and appliances is largely influenced by various kinds of stochastic loading. Regarding to tendency of reducing of energy and material intensity of production and service of machines, over designing of their functional parts is not that best way how to cope negative influences of their running.

It is necessary to find more sophisticated ways; that is for example possibility of controlling (influencing) of activity of appliance during its exploitation. This requires indeed monitoring of reaction of construction on operational load token affect, evaluation of influence of concrete load and consequent real time interventions to activity of appliance.

AUTOREGRESSIVE MODELS AND IDENTIFICATION OF STOCHASTICALLY LOADED SYSTEMS

For realisation of so perceived prevention against undesirable influences of operational load is the first and necessary to identify such stochastically loaded system (real construction, mechanism etc.). That means to obtain its sufficient accurate artificial mathematical model.

Through intended mathematical model of system, sufficient prompt and flexible controlling system of machine and also sufficient software equipment is possible to predicate behaviour of construction in immediate instants of time. This gives us possibility to realise intervention into system activity sooner than its activity will cause unstable state [1, 2].

As appropriate solution for identification of stochastically loaded construction, convenient to requirements on promptness and sufficient accuracy of algorithm of formulation of system dynamic is use of **autoregressive models with moving average ARMA** or their vector modification **ARMAV** (Vectors Auto Regressive Moving Average). Stochastically loaded element of construction of machine in concrete conditions of their use is possible to identify through model ARMA. However, such solution have substantive disadvantage that it enables identification based only on simple time series. That means that loading or oscillation is scanned only in one single point of construction. However by most thorough selection of element or place of construction is practically impossible to sufficiently and accurately represent real behaviour of element as dynamic system during incidence of various operational modes with model obtained by such method [3, 4, 5].

Method to improve adequacy of artificial mathematical model of examined system is use of **vector autoregressive models with moving average – ARMAV** [6]. Models ARMAV are appropriate for identification of mechanism with response on stochastic load scanned currently in more points of system. Basically the point is to find appropriate mathematical solution and realisation of corresponding algorithm, which will use so-called vector time series as input dataset for searched mathematical model (Fig.1).

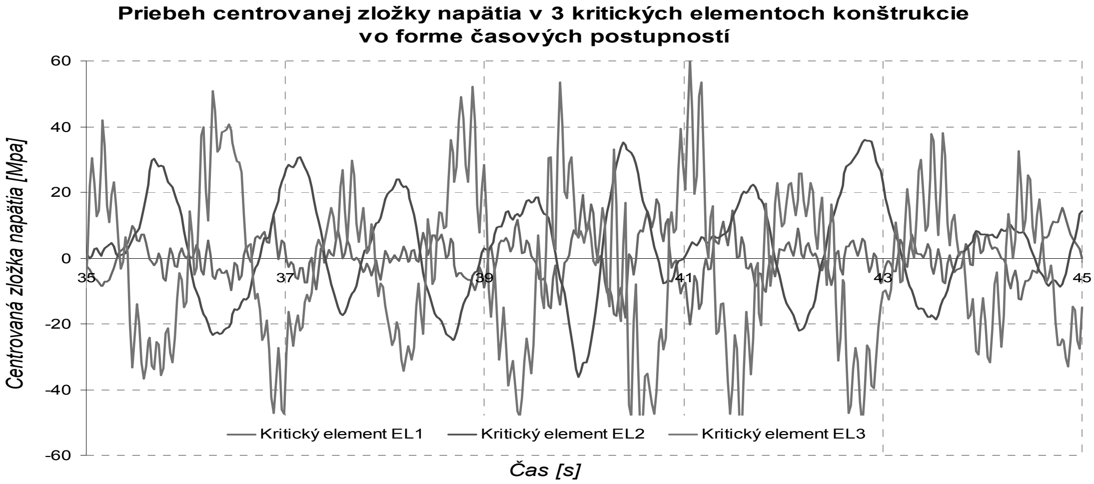

Fig.1 Vector time series

Searched vector mathematical model ARMAV (m, n) is possible to express by vector equation in formulation:

$$\mathbf{X_t} - \mathbf{a_1}.\mathbf{X_{t-1}} - \mathbf{a_2}.\mathbf{X_{t-2}} - \ldots - \mathbf{a_m}.\mathbf{X_{t-m}} = \boldsymbol{\varepsilon}_\mathbf{t} - \mathbf{b_1}.\boldsymbol{\varepsilon}_\mathbf{t-1} - \mathbf{b_2}.\boldsymbol{\varepsilon}_\mathbf{t-2} - \ldots - \mathbf{b_n}.\boldsymbol{\varepsilon}_\mathbf{t-n} \qquad (1)$$

or after itemization of vector equation in formulation [6]:

$$\begin{bmatrix} X_{1t} \\ X_{2t} \\ \ldots \\ X_{kt} \end{bmatrix} - \begin{bmatrix} a_{111} & a_{121} & \ldots & a_{1k1} \\ a_{211} & a_{221} & \ldots & a_{2k1} \\ \ldots & & & \\ a_{k11} & a_{k21} & \ldots & a_{kk1} \end{bmatrix} . \begin{bmatrix} X_{1t-1} \\ X_{2t-1} \\ \ldots \\ X_{kt-1} \end{bmatrix} - \begin{bmatrix} a_{112} & a_{122} & \ldots & a_{1k2} \\ a_{212} & a_{222} & \ldots & a_{2k2} \\ \ldots & & & \\ a_{k12} & a_{k22} & \ldots & a_{kk2} \end{bmatrix} . \begin{bmatrix} X_{1t-2} \\ X_{2t-2} \\ \ldots \\ X_{kt-2} \end{bmatrix} - \ldots$$

$$- \begin{bmatrix} a_{11m} & a_{12m} & \ldots & a_{1km} \\ a_{21m} & a_{22m} & \ldots & a_{2km} \\ \ldots & & & \\ a_{k1m} & a_{k2m} & \ldots & a_{kkm} \end{bmatrix} . \begin{bmatrix} X_{1t-m} \\ X_{2t-m} \\ \ldots \\ X_{kt-m} \end{bmatrix} = \begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \ldots \\ \varepsilon_{kt} \end{bmatrix} - \begin{bmatrix} b_{111} & 0 & \ldots & 0 \\ 0 & b_{221} & \ldots & 0 \\ \ldots & & & \\ 0 & 0 & \ldots & b_{kk1} \end{bmatrix} . \begin{bmatrix} \varepsilon_{1t-1} \\ \varepsilon_{2t-1} \\ \ldots \\ \varepsilon_{kt-1} \end{bmatrix} - \ldots \qquad (2)$$

$$- \begin{bmatrix} b_{112} & b_{122} & \ldots & b_{1k2} \\ b_{212} & b_{222} & \ldots & b_{2k2} \\ \ldots & & & \\ b_{k12} & b_{k22} & \ldots & b_{kk2} \end{bmatrix} . \begin{bmatrix} \varepsilon_{1t-2} \\ \varepsilon_{2t-2} \\ \ldots \\ \varepsilon_{kt-2} \end{bmatrix} - \begin{bmatrix} b_{11n} & 0 & \ldots & 0 \\ 0 & b_{22n} & \ldots & 0 \\ \ldots & & & \\ 0 & 0 & \ldots & b_{kkn} \end{bmatrix} . \begin{bmatrix} \varepsilon_{1t-n} \\ \varepsilon_{2t-n} \\ \ldots \\ \varepsilon_{kt-n} \end{bmatrix} .$$

It is furthermore possible to adjust to system of “k” independent linear equations, in which “k” expresses number of points of construction, where is scanned its response on dynamic load. Left side of vector equation (1) expresses dependence of values of vector time series on previous values, while right side expresses dependence on random deviations vectors.

Use of models ARMAV as alternative to systems of differential equations for identification of stochastically loaded constructions of machines is also convenient for other reason. When we inscribe the system of differential equations in simplified formulation:

$$\mathbf{M}.\ddot{\mathbf{X}}+\mathbf{K}.\dot{\mathbf{X}}+\mathbf{C}.\mathbf{X}=\mathbf{F}(\mathbf{t}) \tag{3}$$

or in matrix formulation:

$$\begin{bmatrix} m_1 & 0 & \dots & 0 \\ 0 & m_2 & \dots & 0 \\ \dots & & & \\ 0 & 0 & \dots & m_n \end{bmatrix} . \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \dots \\ \ddot{x}_n \end{bmatrix} +$$

$$+\begin{bmatrix} k_{11} & k_{12} & \dots & k_{1n} \\ k_{21} & k_{22} & \dots & k_{n2} \\ \dots & & & \\ k_{n1} & k_{n2} & \dots & k_{nn} \end{bmatrix} . \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dots \\ \dot{x}_n \end{bmatrix} + \tag{4}$$

$$+\begin{bmatrix} c_{11} & c_{12} & \dots & c_{1n} \\ c_{21} & c_{22} & \dots & c_{n2} \\ \dots & & & \\ c_{n1} & c_{n2} & \dots & c_{nn} \end{bmatrix} . \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} = \begin{bmatrix} f_1(t) \\ f_2(t) \\ \dots \\ f_n(t) \end{bmatrix}$$

is possible to consider the matrix of absorbing **K** and matrix of springing **C** as mathematical formulation of mutual relations between single elements of described construction. Analogically to that matrix coefficients $\mathbf{a_1}, \mathbf{a_2}, ..., \mathbf{a_m}$ of vector model ARMAV mathematical formulation are mutual relations between particular elements of construction regarding to their interaction by stochastic load in real activity [7, 8, 9].

Advantages of real mathematical models ARMAV are [10]:

1. represent physical subject-matter of real mechanism (i.e. enable to obtain inherent frequencies and inherent forms of oscillations),
2. with required accuracy describe behaviour of real mechanism,
3. mathematical formulation for obtaining of model is relatively simple, sufficiently accurate and entirely possible to transfer by algorithms so, that is possible to control activity of system “in time”.

PRACTICAL APPLICATION OF SUGGESTED IDENTIFICATION METHOD

In contrary to simple ARMA models for type of models ARMAV was not any software application developed up to now and therefore was main aim of authors:

1. to create appropriate software support on the basis of formulated theoretical conditions (software ArmaGet), which enables effective identification of stochastic loaded construction by artificial mathematical model ARMAV,
2. to verify functionality of created software in first phase of testing in simple practical applications of stochastically loaded constructions and to proof adequacy of obtained artificial model of construction.

As applicable mathematical solution for identification by ARMAV-models was created and used vector modification of nonlinear least squares method.

It is evident that creation of software application, which is able to identify stochastically loaded constructions through ARMAV-models, is only the first step to apply predictive control of stochastically loaded mechanical constructions.

Final form of identification software was realised so that part of application which is responsible for execution of identification computations is possible to use in other more complex software application which would identification use as a part of predictive control of concrete mechanism.

For achievement of mentioned requirement was development of software application divided into two phases [6, 12]:

1. Realisation of library of subroutines those are able to apply for required partial calculations of identification. Result - dynamic link library *MatApp.dll*, usable in operating systems MS Windows.

2. Create of software support which is able after setting of required input parameters to use subroutines from *MatApp.dll,* to realise identification of parameters of model and to inform about the result of identification, eventually to archive obtained result. Result – application ArmaGet (Fig.2) is fully compatible with operating systems MS Windows.

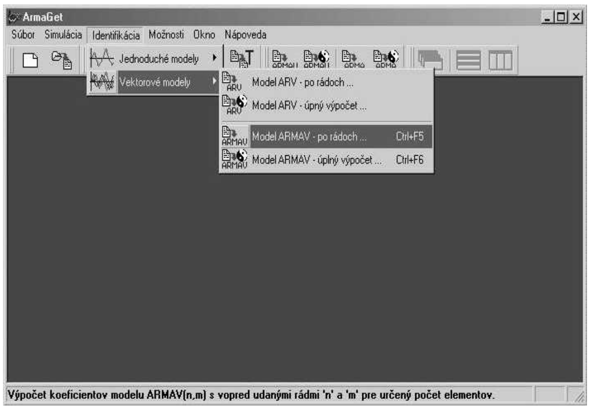

Fig.2 Main window of application ArmaGet

Result of applying of suggested theoretical process was realised as computing software application ArmaGet.

Application is able from input sequence of values (in most cases it is vector time series of response of construction on affecting operational loading) to evaluate matrix coefficients $a_1...a_m$ a $b_1...b_n$. Thus is possible exactly define statistically adequate mathematical model of stochastically loaded system.

In order that vector modification of nonlinear least squares method could be considered as sufficient accurate and resulting parameters of ARMAV models as adequate was necessary to realise its verification.

For this purpose was among other things created FEM (Finite Element Method) model of crane boom and in MATLAB-environment was realised simulation of its loading. Applied loading was defined in form of kinematical excitation of dynamically affecting forces with stochastic course (Fig.3).

By applying of numeric Crank-Nicolson method of direct integration of kinetic equations of model were obtained tensions and shifts occurred along the axes (x, y and z) in all 20 nodes of model. Sampling was proceed in one time interval t ∈ ⟨0,100 s⟩ with step of sampling Δt_{vz} = 0,01 s [6,10].

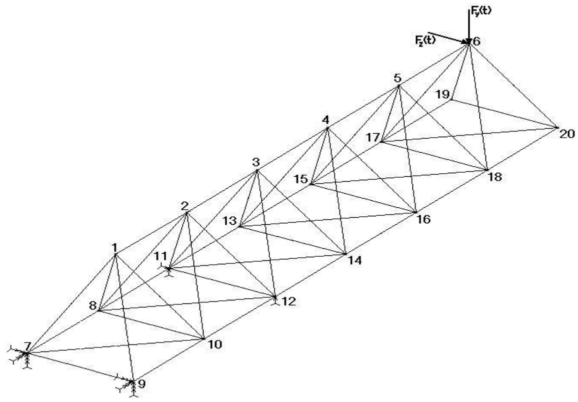

Fig.3 Testing model of crane jib

Resulting shifts in single nodes of construction were sequenced into vector time series. These were used as input data-set for computing of matrix coefficients of ARMAV-models with predefined place values of autoregressive part as well as moving average part (Fig.4).

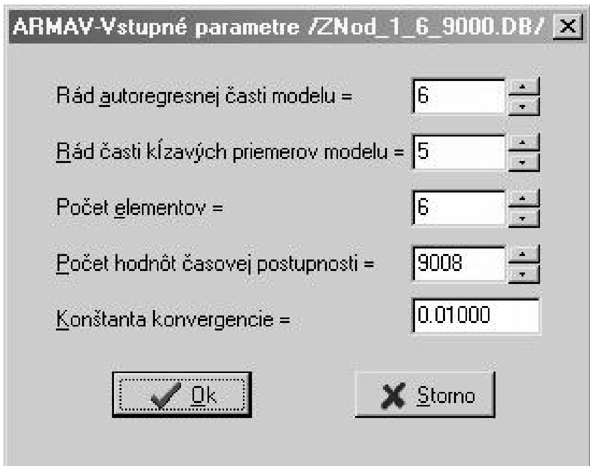

Fig.4 Settings of input parameters for identification process

By means of every so obtained ARMAV-model, were backward simulated new vector time series (totally 3 times for every model).

In testing example was chosen vector time series of shits in nodes 1-2-3-4-5-6 of construction of boom crane along axis “z”, i.e. response of upper boom to kinematical excitation – along the axis “z”. After selection of analysed vector time series, has followed definition of input parameters of identification (Fig.4.).

Example of possible presentation of results of identification for upper boom of model (identified optimal model ARMAV(6,5)) is displayed on Fig.5.

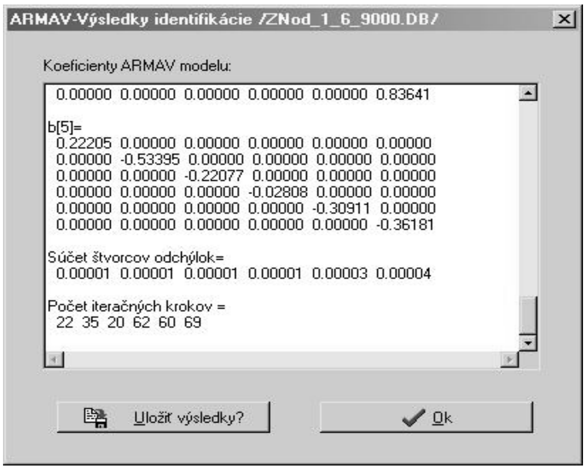

Fig.5 Results of identification of upper boom of crane jib - model ARMAV(6,5)

Verification of functional correctness of application ArmaGet was realised by two different methods. First was applying of computing module *Solver*, which is implemented in table processor *MS Excel*.

As alternative method of verification was used process of generating new vector time series from obtained parameters of ARMAV-model. For this purpose were used "simulating options" of application ArmaGet, which enables generating of new vector time series with identical statistic parameters of first place value and with identical sum of squared deviations. This option is available by main menu item *Simulation→Model ARMAV*.

In Tab.1 are shown results of identification in environment of applications ArmaGet and Excel by means of comparison of values of sum of squared deviations. Further information about used methods and results of verification of processed software are possible to find for example in [2, 3, 5, 7, 10, 11, 12].

Table 1*:* Verification of results of identification (ArmaGet and Excel)

	ARMAV(6,5)		ARMAV(8,7)		ARMAV(10,9)	
		Excel	ArmaGet	*Excel*	*ArmaGet*	*Excel*
Node 1	$7{,}9591.10^{-6}$	$7{,}9606.10^{-6}$	$7{,}9251.10^{-6}$	$7{,}8991.10^{-6}$	$7{,}8985.10^{-6}$	$7{,}8398.10^{-6}$
Node 2	$1{,}0659.10^{-5}$	$1{,}1381.10^{-5}$	$1{,}0493.10^{-5}$	$1{,}1243.10^{-5}$	$1{,}0365.10^{-5}$	$1{,}1953.10^{-5}$
Node 3	$1{,}1204.10^{-5}$	$1{,}2789.10^{-5}$	$1{,}0689.10^{-5}$	$1{,}1868.10^{-5}$	$1{,}0424.10^{-5}$	$1{,}1307.10^{-5}$
Node 4	$1{,}4823.10^{-5}$	$2{,}4128.10^{-5}$	$1{,}4327.10^{-5}$	$2{,}1467.10^{-5}$	$1{,}4028.10^{-5}$	$2{,}0833.10^{-5}$
Node 5	$2{,}5955.10^{-5}$	$4{,}3874.10^{-5}$	$2{,}3396.10^{-5}$	$4{,}2690.10^{-5}$	$2{,}2255.10^{-5}$	$3{,}5906.10^{-5}$
	$4{,}1240.10^{-5}$	$8{,}4167.10^{-5}$	$3{,}8608.10^{-5}$	$6{,}4402.10^{-5}$	$3{,}7822.10^{-5}$	$6{,}2980.10^{-5}$

4. CONCLUSION

Presented article relates with analysis of possibilities of reduction of negative influences of stochastic loading of constructions of building and transport machines on their operation. To process a realisation of prediction of behaviour of loaded construction in concrete conditions of use is necessary to find (identify) its adequate mathematical model [3, 6]. By appropriate mathematical model is possible sufficiently accurate predict behaviour of construction in expected conditions of use. Whether so considered process of reduction of influence of stochastic loading should be usable in practice, is necessary to find and to verify such mathematical solution, which is able "to provide" a artificial mathematic model in real time. Obtained mathematical model must also sufficiently accurate describe behaviour of real system, i.e. must be adequate. On basis of results of prediction if it is necessary it is possible to realise a correction of negative influences sooner than that influences exceed determined range.

It introduces problems were proposed and verified in a frame of grant research, where some possible applications of the proposed identification procedure were investigated. It was namely a connection of proposed identification procedure with systems of complicated machine structures solution using Finite Elements Method [3, 5, 7, 8, 9, 10, 11, 12]. The advantage of using autoregressive models consists of model parameters and modes that can be determined directly from these models not to be necessary to determine transfer functions. In addition, any subjective judgement is eliminated because statistic adequacy tests are exactly defined.

From presented facts one can develop that above shown assumptions and theoretical starting points are correct and developed procedure can reduce number of calculation in an expressive way and improve efficiency of mechanical structures dynamic calculation.

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Reviewer: prof. Dr. Ing. Milan SÁGA

ПРОГРАМНО ОСИГУРЯВАНЕ НА ИДЕНТИФИЦИРАНЕТО НА СТОХАСТИЧНО НАТОВАРЕНИ ЧАСТИ ОТ МЕХАНИЧНИ КОНСТРУКЦИИ

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Резюме: *В статията се описва възможен начин за идентифициране на стохастично натоварени механични конструкции на машини за целите на прогнозен контрол на тяхната дейност в условия на реално натоварване. Конкретно докладът се отнася до проект за приложение на модели на векторна авторегресия (ARMAV), чиито параметри могат да се идентифицират чрез приложението на векторна модификация на метода на нелинейните най-малки квадрати. Статията съдържа теоретична основа за решени задачи, описавие на реализация на тестване на метода и кратка интерпретация на проверените резултати от функционално обработена програма и точно получени изчисления..*

Ключови думи : *Механични конструкции, стохастичен товар, авторегресивни векторни модели, програмно осигуляване на идентифицирането – ArmaGet, проверка на резултатите от идентификацията*