INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

DESIGN 2004

A NEW METHOD FOR SELECTION AND DESIGN OF COMPOSITE ELEMENTS FOR IMPACT LOADING

K. Dobrucki and R. Rohatyński

*Keywords: composite elements, impact loading, shock attenuation,
simulation of kinetic reaction, design*

1. Introduction

Impact (shock) loadings belong to a particular class of dynamic loads of mechanical systems. They lead to damages, thus they are very undesirable. Perhaps the most spectacular cases happen in vehicles, where road accidents not only cause car damages but also pose a serious threat to people's lives. Special constructions have been devised in order to absorb the shock energy and to protect the human body from the accident effects. Intensive and extensive research for bumpers and other mechanical units are carried out in many laboratories all over the world. They are strongly supported by the automotive industry.

Locally applied strokes generate waves which propagate and in various forms come back after reflection. Aspects of dynamic load interactions, including collision of solid bodies are described in many papers, e.g. [Tate 1967, Zukas, Nicholas Swift, Greszczuk, Curran 1982]. Wave phenomena and effects have been also described in details [Ziółko 2000, Radowicz 1994]. The authors' contribution to the problem consists in the method of designing the material properties that guarantee the required dynamic response of a composite structure [Dobrucki 2001]. In engineering practice the problem of impact resistance is solved by applying heavy elements and conventional metal materials. As the result, elements exposed to the strokes have less deflection, but are too heavy. To adapt mechanical structures for bearing of strong impacts, it is necessary for them to have a margin of endurance and stiffness. Moreover, it is not enough to specify the endurance characteristics. It is also important to ensure appropriate trajectory of recovering to the stationary state. In this respect the material that effects in extending time of the element response to the impact can be regarded as better.

Thus, there is a need to a new approach to the design of the composite bumpers and other elements of similar functions. The approach should include an effective method of determination of the element damping characteristics. It is also known that to design a good mechanical composite system for shock absorbing it is not enough to know its standard strength characteristics. The response of a composite system to impact significantly depends on the composite structure. This paper concerns only determination of improved characteristics of the element. Further research is aimed at the identifying such a fiberglass structure in the polymer composite element that would meet these improved characteristics. This research is not reported here.

2. Outline of the method

In the presented method identification of the interactive mechanical system characteristics and prototyping of its shock absorption capability are integrated in search of a feasible mechanical system that meets specified requirements (fig. 1). The set of the requirements for dynamical properties establish the basis for object-oriented modeling of mechanical systems. Experimental test procedure, prototypes making, and setting up the research stand are used for investigation of kinetics phenomena caused by bending impact.

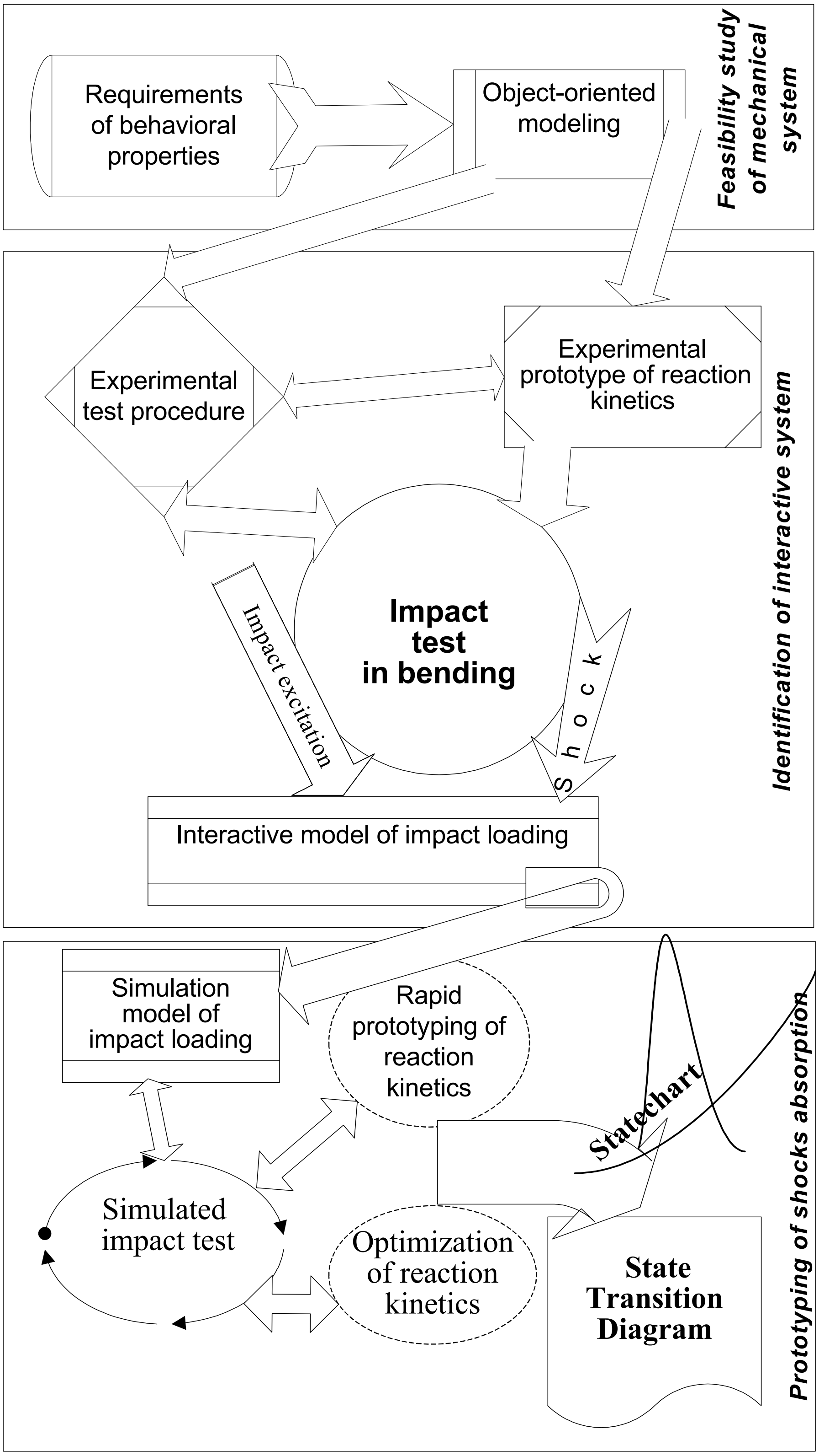

Figure 1. The method for selection and design of elements for impact loading

The following assumptions have been made:

- environmental conditions are independent on the mechanical system under investigation,
- parameters of subsystems are lumped and not changing in time,
- noise impulses are very small and can be neglected,
- input and output variables, start-up conditions and values of system parameters as well as their deviations and disturbances are observable functions of time.

Motion of the impacted elements can be seen as consisting of three subsequent phases. The first one bears the most information of the element absorption capability, thus it is the most important from the viewpoint of our method. Identification of a purposefully modeled research object is called the active identification [Uhl 1990]. This kind of identification - with the use of the Heaviside's statement [Heaviside 1984] - is applied to prototyping of kinetic properties of the stroked mechanical elements. Experimental tests of impact provide data for calculation a matrix of impact interaction. Interactive model of impact loading is defined with Output *Error oe221 model* estimator (for more information see: MATLAB. The MATH WORKS, Inc. Version 5, Nonlinear Control Design Block Set):

$$y(t) = [B(q^{-1})/F(q^{-1})]\, u(t\text{-}nk) + e(t) \tag{1}$$

$$F(q^{-1}) = f_0 + f_1\, q^{-1} + ...+ f_{na}\, q^{-na}\,; \qquad B(z^{-1}) = b_0 + b_1\, q^{-1} + ... + b_{nb}\, q^{-nb} \tag{2}$$

Having estimated the oe22 model the prototyping of shocks absorption process is possible. Simulation of impact loading and simulation of impact effects are the basic elements of rapid prototyping of shock absorption in mechanical systems. The whole process of identification is depicted in figure 1. A nonlinear programming method for constrained functions is applied to choice the optimal search directions. The sequential quadratic programming method is used to find the feasible constrained transfer function. In the quadratic programming problem the objective function is represented as a Hessian matrix, which is updated according to the modified directions. The task to find improved search direction can be expressed by the following formulae [Zalewski, Cegieła 1996]:

$$\min 0{,}5\; \mathbf{d}^T \mathbf{Ad} + \nabla f(\mathbf{x}_k)^T\, \mathbf{d} \qquad \text{where } \mathbf{d} \in R^n \tag{3}$$

$$\nabla g_i(\mathbf{x})^T d + g_i(\mathbf{x}) = 0 \qquad i = 1, ..., m_e \tag{4}$$

$$\nabla g_i(\mathbf{x})^T d + g_i(\mathbf{x}) \leq 0 \qquad i = m_{e+1}, ..., m \tag{5}$$

The condition of the feasibility of a corrected direction is $\mathbf{d} \in D(\mathbf{x})$. The search starting point $\mathbf{x}_t$ is determined by the identified model parameters, for example K, ζ, ω_0 in (6). Optimized values of these parameters can serve the choice of the internal structure of composite materials.

In the next section an example of the method application to improving of the element characteristics is presented.

3. Example of implementation

Application of the method is shown on a prototyping of impact kinetics of a composite beam. The beam was made of epoxy resins reinforced by fiberglass (the composite subsystem M5TV234). It was subjected to bending impact. The wave of impact stress (see *Input* in fig. 2) as well as the deflection of the beam (see *Output* in fig. 2) were recorded. Details of the measuring system have been described elsewhere [Dobrucki, Romanow 1995,1999].

As the result of the identification procedure [Heaviside 1984, Uhl 1990], that was outlined in the previous section, the operator transfer function G(s) is determined, which represents dynamic behaviour of the investigated system. According to this, properties of a real mechanical element are mapped by the operator transfer function.

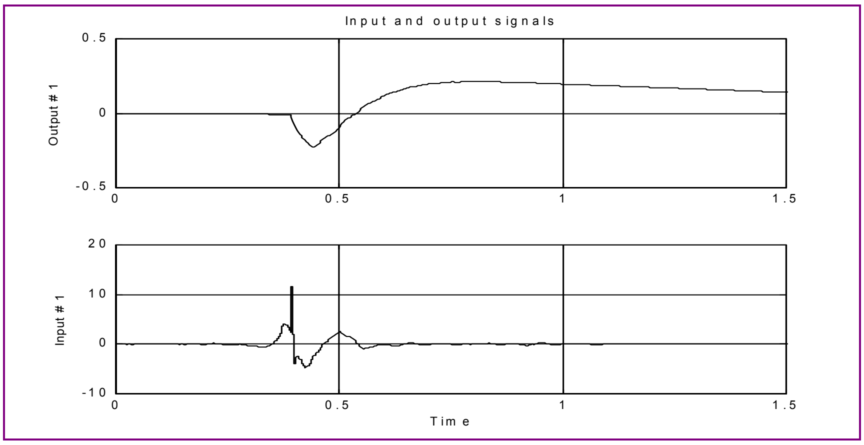

Figure 2. Displacement of the composite element (Output) resulting from impact excitation (Input)

In the given example this procedure yielded the results presented in table 1.

Table 1. Result of identification procedure. Model oe 221 for the composite system M5TV2344

Linear equation of state	dx/dt =A x + B u y = C x + D u
Matrixes	A = 1.0; C = 1,0; D = 1,0
B =	0 0.0016 -0.0017 0 0.0008 0.0008
F =	1 -1.9968 0.9999 0 0.0066 0.0066
Transfer function	G(s)=(0.5383s–9.4724)/(s^2+0.0292s+347.8043)
	G(s)=0.5383*(s–17.5984)/(s–p1)*(s–p2)

The next step consists in the determination of improved material characteristics. This task is carried out by an optimization procedure. The optimization aims at modification of the system frequency and of the damping coefficient so that dynamic trajectory of deformation after a single impact u(t) would satisfy the given requirements. In this example, optimization of material characteristics is carried out for definite time intervals, for which the element deformation are expressed by the transfer function:

$$G(s) = \frac{-K(as+b)}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \qquad (6)$$

This can be regarded as the equation of state of the mechanical system. To find out its coefficients, which would ensure an assumed transient response a simulation model of the system oe 221 M5TV234 was built (figure 3). The search proceeds by means of the method of modified directions. The objective function for quadratic programming problem contains a Hessian matrix which has been updated according to the modified direction, as it was mentioned in the previous section. After the right direction has been found out the minimization according to this direction is performed.

The search starts from the point $\mathbf{x}_t$ (K, ζ, ω_0), in which values of the parameters of equation (6) are the input The following input values were taken for the composite beam prototype under investigation: amplitude of impact loading K=50, damping coefficient ζ=0,1 and natural frequency ω_0=10. Time range for the composite element deformation after shock was specified as 10 > t > 0. Time T1, T2, T3 and local values u1,u2, u3 of the element deformation constraints were determined as follows: {0 <T1 < 1; - 0,11 < ul < 0,14}; {1 < T2 < 2; - 0,07 < u2 < 0,25};{ T3 > 2; 0,14 < u3 < 0,16}.

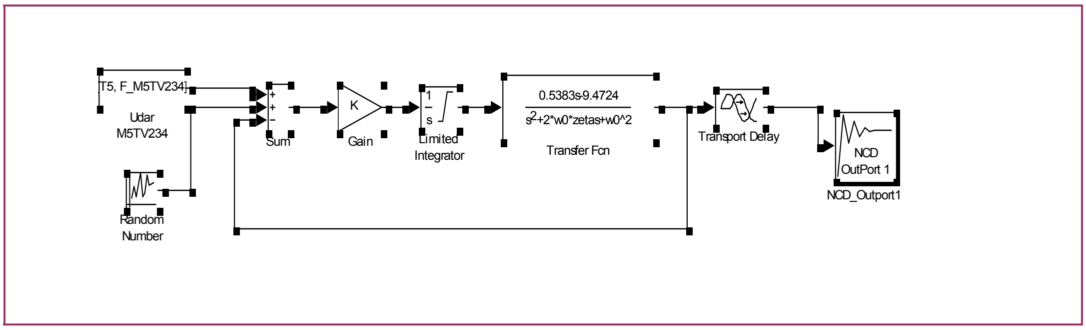

Figure 3. Simulation model of mechanical composite system oe 221 M5TV234

Then values of parameters for simulation model were computed. As a result of the applied optimization procedure the amplitude of the prototyped composite beam has not been changed, K = 50. Natural frequency ω_0=9,91 decreased a little, whereas the value of damping coefficient increased ca three times, ζ=0,3141.

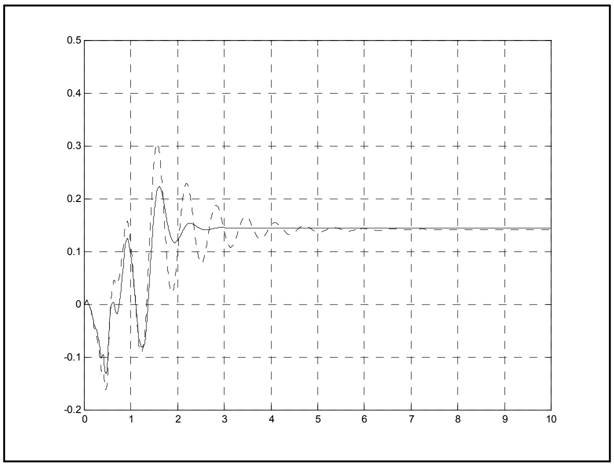

Figure 4. The beam deformation trajectory original (dashed) and optimized (full)

Figure 4 shows that the amplitude of the optimized beam deflection (full line) has been significantly decreased in comparison with the original one (dashed line). The prototyped mechanical system returns to the static equilibrium twice faster.

4. Conclusions

The paper deals with the problem of designing materials for machine elements exposed to shock loadings. The necessity of designing of mechanical elements kinetic properties by means of modified engineering materials has been emphasized. A new, experimental but theoretically based method for prototyping characteristics of machine elements exposed to shock hazards is presented. This method enables selection and/or designing of mechanical systems, which absorb strokes effectively.

Numerical prototyping of impact kinetics and optimalization of state equations parameters have been integrated. A procedure to achieve the improved static and dynamic characteristics of the damping element has been shown by the illustrative example.

This paper concerns only with the determination of improved characteristics of the investigated element. The research that has hitherto been carried out on simple mechanical elements made from several types of composites has confirmed the method applicability. The research is in progress. The subsequent research aims at searching for the composites that make the required characteristics real.

References

Dobrucki, K.," A method of designing of polymer composites for impact loading", 10 The Jubilee International Scientific Conference Achievements In Mechanical & Materials Engineering,. AMME 2001, Gliwice 2001..

Dobrucki, K. Romanow, F., „Doświadczalna identyfikacja charakterystyk drgań kompozytowych belek wspornikowych", Raport wewnętrzny,Politechnika Zielonogórska,1999, (Experimental identification of vibration characteristics of the composite cantilever beams).

Heviside, O.," Electrical Papers", Bd I, s.520, BdII, S.202,1984.

MATLAB. The MATH WORKS Inc. Version 5,Nonlinear Control Design Blockset. Simulink, MATLAB. The MATH WORKS, Inc. Version 5.

Radowicz,, A., „Fale powierzchniowe", Wydawnictwo Politechniki Świętokrzyskiej, seria Monografie, Studia Rozprawy, Kielce,1994,(Surface waves).

Romanow, F., Dobrucki, K., „System pomiaru i analizy tłumienia drgań belek kompozytowych", XVII Sympozjon PKM Lublin,1995, (A system for measurement and analysis of composite beam vibration).

Uhl, T., „Identyfikacja układów mechanicznych podlegających zderzeniom" Zeszyty Naukowe Mechanika 25, AGH Kraków, 1990,(Identification of mechanical systems subjected to shocks).

Tate, A., " A theory for the deceleration of long rods after impact", J.Mech.Phys. Solids, 15, (1967).

Zalewski, A., Cegieła, R., „ MATLAB –obliczenia numeryczne i ich zastosowania", Wydawnictwo Nakom. Poznań,1996, (MATLAB – numerical calculation with application).

Ziółko, M., „Modelowanie zjawisk falowych", AGH Kraków, 2000, (Modeling of wave phenomena)

Zukas, J.A., Nicholas, T., Swift H.F.,Greszczuk L.B., Curran D.R., "Impact dynamics" , A wiley-Interrscience Publication, New York 1982.

Table of symbols

T	*Time constant*
$\mathbf{A}$	*State matrix*
B	*Matrix of inputs*
C	*Matrix of outputs*
D	*Transmittance matrix*
$F(q^{-1})$	*Polynomial of* q^{-1}
$y(t)$	*Trajectory of response of system* $[m*10^{-3}]$
$u(t)$	*Trajectory of stimulation of system*
$e(t)$	*Influence of environment (white noise)*
n_k	*Number of delay tacts*
q^{-1}	*Operator of delay for one probing period*
K	*Gain coefficient*
$\mathbf{d}$	*Direction vector*
A	*Hessian of target function*
$\mathbf{x}_t$	*Vector of searched variables*
g_i	*Inequality constraints*
m	*Number of constraints*
m_e	*Number of equality constraints*
$D(x)$	*Set of admissible directions,*
ζ	*Damping coefficient,*
t	*Time [second]*
ω_0	*Natural frequency*

Ryszard Rohatyński
University of Zielona Gora, Department of Mechanical Enginering
65-246 Zielona Gora, ul. Podgorna 50, Post Box 47, POLAND
Telephone: +48 68 3282546, Telefax: + 48 68 3270735
E-mail: R.Rohatynski@iizp.uz.zgora.pl