Dynamic Pattern of Safe Operation Indicators for Heavy-Duty Machines

Yu. A. Izvekov, V. V. Dubrovsky and A. L. Anisimov

Abstract This article studies the dynamic pattern of safe (hazardous) operation indicators for heavy-duty machines. A load-carrying structural member of metallurgical overhead crane with a frame manufactured from 09G2S steel and having 50 ton lifting capacity was selected for the study. A generalized limit-state equation for the structural crane element represents hypersurface, which distinguishes the safety zone and the hazard zone. Safety and hazard functions are presented as integral functions of probability distribution density, resulting from various factors that affect the likelihood of occurrence of emergencies, accidents and machine breakdowns. The indicators with the greatest influence on the probability of safe and hazardous states of the structural element or the structure itself can be identified. It is accepted to investigate probabilistic features of stress and deformation fields. The stochastic boundary-value problem of the structural element's stress–strain behaviour under random load is addressed in this case. The problem can be resolved by obtaining correlation and spectral functions of stress and deformation under given load functions. Considering that heavy-duty machines are operated in steady state, it can be assumed with sufficient assurance that such random processes represent steady Gaussian processes. The probabilistic dynamics of safe operation indicators are studied by using computer-based simulation modelling. The obtained modelled curves of probabilistic machine load allowed one to deduce equations of stress and deformation probability density. Every coefficient of the obtained models is probably significant based on Fisher's criterion. The obtained relationships allow one to construct graphs of limit and acceptable states when evaluating durability and operating life of heavy-duty machines and the probability density for operating and rupturing loads and stresses.

Keywords Safe operation · Heavy-duty machines · Random processes · Probability density · Limit-state graph · Stress · Deformations

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1 Introduction

Heavy-duty machines operate in severe environment with, normally, high stresses and deformations, sudden temperature changes, multitude cycles, long service life and continuance of defect concentration. All these factors are associated with risks of accidents and emergencies that can be resulted from operating such machines. Therefore, it is important to study the dynamic pattern of safe operation indicators from the perspective of the system's probabilistic dynamics.

2 Study Purpose

Based on the concepts described in [1–3], the following generalized limit-state equation for the rupture zone of a structural loaded heavy-duty machine's element can be generated:

$$F\left(\sigma_{ij}, \varepsilon_{ij}, l, N, t, T\right) = 0 \tag{1}$$

where σ_{ij}—stresses; ε_{ij}—deformations; l—defect type and dimensions; N—number of cycles; t—service life; and T—temperature.

Equation (1) represents hypersurface, which distinguishes the safety zone and the hazard zone.

By entering n-dimensional probability distribution density $f\left(\sigma_{ij}, \varepsilon_{ij}, l, N, t, T\right) = f(X)$, functions of safety and hazard can be presented as follows:

$$P_{\mathrm{S}}(t) = P\left\{F\left(\sigma_{ij}, \varepsilon_{ij}, l, N, t, T\right)\right\} = \int f(X)\mathrm{d}X; \tag{2}$$

P_{S} is the probability of safe state (time-based function);

$$P_{\mathrm{R}}(t) = 1 - P\left\{F\left(\sigma_{ij}, \varepsilon_{ij}, l, N, t, T\right)\right\} = 1 - \int f(X)\mathrm{d}X; \tag{3}$$

P_{R} is the probability of hazard (hazardous state, time-based function).

Thus, the purpose of this article is to quantitatively study the above functions.

3 Study Materials and Methods

The presented formulas enable to evaluate the hazard of out-of-limit stresses, deformations, defects, temperatures, number of cycles and service life in terms of structure-related risk analysis [4–7] from the perspective of rupture and safety [8–25].

Identifying probabilistic properties of potential rupture zones as a compatible function of probability distribution $f\left(\sigma_{ij}, \varepsilon_{ij}, l, N, t, T\right)$ represents quite a time-consuming task. By using principal component analysis, indicators with the greatest influence on the probability of safe and hazardous states of the structural element or the structure itself can be identified. It is accepted to investigate probabilistic features of stress and deformation fields. The stochastic boundary-value problem of the structural element's stress–strain behaviour under random load $q(t)$ is addressed in this case. The problem can be resolved by obtaining correlation and spectral functions of stress and deformation under given load functions.

The properties of functions $f(\sigma_{ij}, t)$,$f\left(\varepsilon_{ij}, t\right)$ can be described by making a certain assumption about the nature of random processes. Considering that heavy-duty machines are operated in steady state, it can be assumed with sufficient assurance that such random processes represent steady Gaussian processes with the following expectation values:

$$\sigma_{ij} = \int\limits_{-\infty}^{\infty} \sigma_{ij} f\left(\sigma_{ij}\right) \mathrm{d}\sigma_{ij}, \tag{4}$$

$$\varepsilon_{ij} = \int\limits_{-\infty}^{\infty} \varepsilon_{ij} f\left(\varepsilon_{ij}\right) \mathrm{d}\varepsilon_{ij}, \tag{5}$$

and dispersions:

$$\sigma_{ij}^2 = \int\limits_{-\infty}^{\infty} \sigma_{ij}^2 f\left(\sigma_{ij}\right) \mathrm{d}\sigma_{ij}, \tag{6}$$

$$\varepsilon_{ij}^2 = \int\limits_{-\infty}^{\infty} \varepsilon_{ij}^2 f\left(\varepsilon_{ij}\right) \mathrm{d}\varepsilon_{ij}. \tag{7}$$

Probability distribution density in this case is subject to the normal law of distribution:

$$f\left(\sigma_{ij}\right) = \frac{1}{\sqrt{2\pi\sigma_{ij}^2}} \mathrm{e}^{\frac{-\left(\sigma_{ij}-\sigma_{ij}\right)^2}{2\sigma_{ij}^2}}, \tag{8}$$

$$f\left(\varepsilon_{ij}\right) = \frac{1}{\sqrt{2\pi\varepsilon_{ij}^2}} \mathrm{e}^{\frac{-\left(\varepsilon_{ij}-\varepsilon_{ij}\right)^2}{2\varepsilon_{ij}^2}}. \tag{9}$$

Calculations will be made for the heavy-duty production equipment element—i.e. the supporting frame of the metallurgical overhead crane with 50 ton lifting capacity. The supporting frame of the crane during load lifting, movement and lowering is subject to varying effective bending stresses, which represents random steady-state differentiated process with normal distribution. Frame material is 09G2S steel. Normal constant expectation values of stresses σ_{ij} and deformations ε_{ij} equal 165 MPa (megapascal) and 0.785×10^{-3}, respectively; dispersion $\sigma_{ij}^2 \approx$ 8300 MPa^2, (megapascal^2) limit stresses ≥ 256 MPa (megapascal) and limit deformations equal 1.219×10^{-3}. Probabilistic dynamics of safe operation indicators will be studied by using simulation modelling.

4 Study Findings and Their Discussion

Hence, the dynamics of safe and hazardous operation indicators can be presented as follows:

$$P_S(t) = P\{F(\sigma_{ij})\} = \int \frac{1}{\sqrt{2\pi\sigma_{ij}^2}} e^{\frac{-(\sigma_{ij}-\sigma_{ij})^2}{2\sigma_{ij}^2}} d\sigma_{ij}; \tag{10}$$

$$P_S(t) = P\{F(\varepsilon_{ij})\} = \int \frac{1}{\sqrt{2\pi\varepsilon_{ij}^2}} e^{\frac{-(\varepsilon_{ij}-\varepsilon_{ij})^2}{2\varepsilon_{ij}^2}} d\varepsilon_{ij}; \tag{11}$$

$$P_R(t) = 1 - P\{F(\sigma_{ij})\} = 1 - \int \frac{1}{\sqrt{2\pi\sigma_{ij}^2}} e^{\frac{-(\sigma_{ij}-\sigma_{ij})^2}{2\sigma_{ij}^2}} d\sigma_{ij}; \tag{12}$$

$$P_R(t) = 1 - P\{F(\varepsilon_{ij})\} = 1 - \int \frac{1}{\sqrt{2\pi\varepsilon_{ij}^2}} e^{\frac{-(\varepsilon_{ij}-\varepsilon_{ij})^2}{2\varepsilon_{ij}^2}} d\varepsilon_{ij}. \tag{13}$$

Simulation findings are presented in Figs. 1 and 2.

The obtained modelled curves of probabilistic machine load enabled to deduce the following probability density equations:

$$f(\sigma_{ij}) = 0.008e^{-0{,}006\sigma_{ij}}, \tag{14}$$

$$f(\varepsilon_{ij}) = 0.597e^{\varepsilon_{ij}}. \tag{15}$$

Every coefficient of the obtained models is probably significant based on Fisher's criterion.

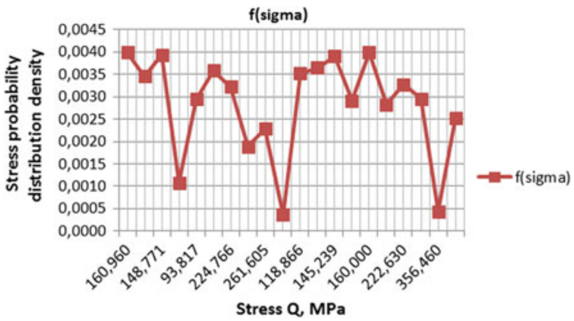

Fig. 1 Probability distribution density as function of effective stresses

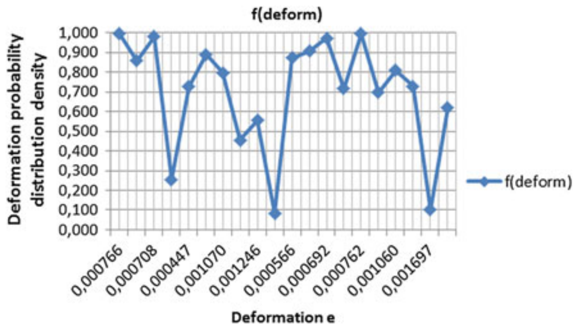

Fig. 2 Probability distribution density as function of deformations

Hence, the dynamic pattern of safe operation indicators for the heavy-duty machine elements under study can be formulated as follows:

$$P_{\mathrm{S}}(t) = P\{F(\sigma_{ij})\} = \int 0.008\mathrm{e}^{-0.006\sigma_{ij}}\mathrm{d}\sigma_{ij}; \tag{16}$$

$$P_{\mathrm{S}}(t) = P\{F(\varepsilon_{ij})\} = \int 0.597\mathrm{e}^{\varepsilon_{ij}}\mathrm{d}\varepsilon_{ij}; \tag{17}$$

$$P_{\mathrm{R}}(t) = 1 - P\{F(\sigma_{ij})\} = 1 - \int 0.008\mathrm{e}^{-0.006\sigma_{ij}}\mathrm{d}\sigma_{ij}; \tag{18}$$

$$P_{\mathrm{R}}(t) = 1 - P\{F(\varepsilon_{ij})\} = 1 - \int 0.597\mathrm{e}^{\varepsilon_{ij}}\mathrm{d}\varepsilon_{ij}. \tag{19}$$

The resulting relationships allowed to construct the graphs of limit and acceptable states when evaluating durability and operating life of heavy-duty machines and the probability density for operating and rupturing loads and stresses, as shown in Fig. 3.

Dips in the above graph represent potentially hazardous zones of risk, when operating or rupturing stresses and deformations exceed limit values.

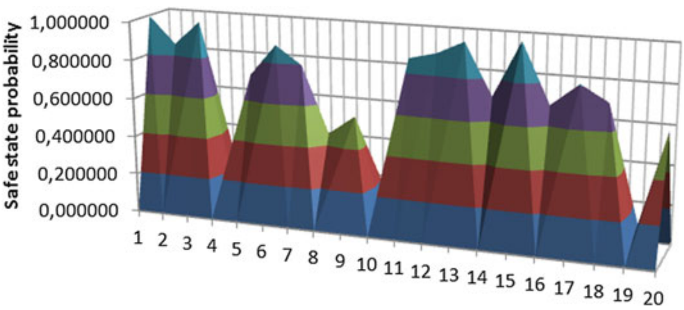

Fig. 3 Graphs of limit and acceptable states for operating and rupturing stresses and deformations

5 Conclusions

The presented multidisciplinary approach to evaluating the dynamics of safe operation indicators for heavy-duty machines represents promising area of risk analysis. This is particularly important when quantitative safety or hazard evaluation is required.

Considering that the identification of probabilistic properties of potential rupture zones as a compatible function of probability distribution represents quite a time-consuming task, it was accepted to study probabilistic properties of stress and deformation fields. Mathematical apparatus of stochastic process was applied in this study.

The equations of safe and hazardous operation functions for the heavy-duty structural element of metallurgical overhead crane—i.e. the frame manufactured from 09G2S structural steel with its known mechanical properties and limit loads—were deduced. Popular mathematical apparatus of nonlinear regression was used. The models were probably significant. The graph of limit and acceptable states for operating and rupturing stresses and deformations were presented based on the analysis of obtained equations of structure-related probabilistic dynamics.

The obtained results demonstrate functionability of risk analysis for different structures and, certainly, constitute useful materials for executive operators of such machines, engineers and researchers. Safe operation of heavy-duty machines results in the improvement of their quality and, consequently, economic efficiency.

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