ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

ENERGETIC CHARACTERISTICS OF VIBRATION LOADS ON A MECHANICAL OBJECT

Prof. dr hab. Henryk KAŹMIERCZAK, dr Jacek KROMULSKI,
dr ing. Tadeusz PAWŁOWSKI

Industrial Institute of Agricultural Engineering, ul. Starołęcka 31, 60-963 Poznań, Poland
kazmhenr@pimr.poznan.pl

Abstract

Unwanted dynamic reactions (vibrations) disorganize a machine functionally and structurally and determine changes in its technical condition.
Dynamic properties of a machine are a derivative of spatial distribution of machine physical properties and boundary conditions as well as the way of connecting it with the prime mover.
In the study of energetic profiles of vibration loads in a machine, the method of dynamic susceptibility is applied to build the analytical model of the system, and the method of experimental modal analysis is used to identify machine dynamics profiles.
The paper presents the application of the analysis method for distribution of dynamic load powers to describe the technical condition of an object and the degradation process of a mechanical object. The method of energetic modelling for machine vibration loads helps to establish separately the power of dumping forces and inertia forces, and dynamic stiffness forces in a complex mechanical system. This method allows assessment of the impact of particular input functions and components of force power spectra on the life curve of an object. It can also be a method of experimental review for numerical strength models obtained by finite element methods. The knowledge of spatial load distribution in a mechanical object in the functions of frequency and operating time helps identify elements that are subject to overloads. Changes proposed on the basis of vibration load analysis help avoid overloading and braking machine components.

1. INTRODUCTION

This paper presents spatial, energetic characteristics of vibration loads, describing diagnostic conditions of specific machines. The method is applied in analyzing energy dissipation and structural changes in mechanical objects. The method takes into account spatial changes of energy in individual subsystems as well as energy flow between those subsystems. Through analyzing energy density distribution in each subsystem, spatial change of vibration response is obtained (in the areas of acceleration, stress, acoustic pressure etc.). In order to assess the dynamic condition of a machine, knowledge of dissipated power is

required (real parts of dynamic load power) as well as separation of the power of inertia force and dynamic rigidity power (imaginary parts of dynamic load power). A synthesis of spectral characteristics for the loads was made by decomposing characteristics matrices into singular values, whereby estimates of dominating spectra of power spectral density of machine mechanical loads were achieved. Dominating singular spectra of the power matrix were determined for machine dynamic loads, its real and imaginary parts. Along with the increase of dynamic loads, interrelations between the power of rigidity and damping forces change.
In the research, spectral power characteristics of dynamic loads were specified for a rolling press and wood chipping machine. Energetic characteristics of dynamic loads on the wood chipping machine are of impulse character. The structure of the machine is compact. Dynamic load powers for specific structural nodes vary. Dynamic inertance in various points of the machine were specified. Linear properties of machine structure were found in a broad frequency range and large range of amplitudes.

2. CHARACTERISTICS OF THE DEGRADATION PROCESS FOR A MECHANICAL OBJECT EXPOSED TO EXTERNAL FORCING VECTOR

In the time function of machine operation the machine is exposed to the process of evolutionary destruction resulting from excessive loads and fatigue of structural members, and wear related to friction (play) etc. The goal of the testing research is to identify a failure risk or a condition that directly leads to a failure. The issue of assessing the technical condition of a machine amounting to the monitoring of machine degradation is based on the energy processor model. The method used for testing the characteristics of life time degradation of a spatial object (physical model) exposed to multiple variable forcing actions, helps specify the spectral load components which provide information about the progressive technical degradation process of an object. Applying the analysis of dynamic load power distribution to the process of mechanical object degradation, provides a modern, energetic method of reliability and life time analysis for an object. It also allows an assessment of influence exerted by specific forcing actions and components of power spectra of degradation forces on life time characteristics of an object. It can also be a method of experimental review for numerical durability models achieved by finite element method (FEM).

The knowledge of spatial distribution of loads on a mechanical object in the functions of frequency and operation time, helps identify components exposed to overloads (exceeding the limiting tension values). It will also help assess and forecast their technical condition. Changes proposed for the structural characteristics help avoid overloads and damaging machine components.

The proposed method of energetic modelling of machine degradation verifies the need to consider, on a separate basis, dissipated energy and the power of inertia and dynamic rigidity forces in a complex mechanical system. The method takes into account the synergy of factors affecting the degradation of a structure: corrosion, fatigue, environmental influence (humidity), temperature, non-homogeneous structure.

Throughout machine operation time numerous phenomena take place and change its technical condition (life time and reliability). Cracking is the most dangerous result of energy dissipation in the structural material of the machine and it leads to unpredictable kinetic nodes introducing additional degrees of freedom causing deterioration of structural functions. Variable stresses caused by vibrations focus on the edges of gaps and material defects. As a result, energy dissipation in the material is also focused in those spots. Propagation of material defects resulting from variable stresses produces fatigue scrap. Input data for the optimization system are obtained from machine operation and accelerated hands-on tests of the machine or its components. Machine components are frequently exposed to regular bending or twisting loads, or both of these at the same time, as well as static loads (weight and preload loads) linked to machine functions. These loads cause material fatigue processes at spots of stress accumulation.

3. DETERMINING FATIGUE-RELATED LIFE TIME OF A MACHINE USING THE METHOD OF SPECTRAL ANALYSIS OF DYNAMIC LOAD POWER DISTRIBUTION. CHARACTERISTICS OF MACHINE DEGRADATION PROCESS

The life time of a machine being a complex system is affected by dynamic properties of its components, as well as materials of which it is made. Deterioration of a mechanical system is linked to changes in its structural properties, and these occur because of energy, being the difference between input work and useful work in a mechanical system. Energy dissipation is caused by the processes of external and internal friction as well as permanent material distortion. Taking into account the fact, that some dissipated energy is dispersed in the form of heat, it is possible to determine very precisely the energy causing permanent distortion of specific machine components. This energy is the cause of fatigue destruction of material.

Criteria covering phase differences between distortion and stress components can be classified in a number of ways. One of them is to split them by the type of parameters adopted to describe the fatigue process. There are three groups of criteria: stress, distortion and energy related.

According to the Huber strength hypothesis formulated in 1904 material destruction depends on the critical specific energy value of non-dilatational strain.

For small non-dilatational strains in material, the energy of non-dilatational strain is close to energy in linearly elastic material, and therefore physical properties of material will, in the initial phase of distortion, be similar to physical properties of linearly elastic materials, which is characteristic of most popular materials of high practical significance and used as construction materials.

The state of dynamic (vibration) loads on a machine is described by the matrix of power spectral density of dynamic load powers in a mechanical system [2]:

$$\{\mathrm{GN}_{ik}(\mathrm{j}\omega,\Theta)\} = \mathbf{H}_{V_{ik}}(\mathrm{j}\omega,\Theta)\cdot\mathbf{G}_{F_kF_k}(\mathrm{j}\omega,\Theta) \tag{1}$$

where: $\mathbf{H}_{V_{ik}}(j\omega,\Theta)$ – the matrix of dynamic mobility of a system,

$\mathbf{G}_{F_kF_k}(j\omega,\Theta)$ – the matrix of spectral density of forcing actions.

The powers $\mathrm{Re}\,\overline{\mathrm{GN}}_{kk}(\Theta)$, being real values, are a measure of dissipated powers; the powers $\mathrm{Im}\,\overline{\mathrm{GN}}_{ik}(\Theta)$, $i \neq k$, are force powers of dynamic rigidity and inertia of mechanical structures transferred to spots "*i*".

4. EXAMPLES

4.1 Energetic characteristics of dynamic loads on a hay silage rolling press. Dominating input power characteristics of press dynamic loads

Figure 1 displays spectral characteristics of dynamic load powers on the press in point 1, determined during hay silage pressing.

In a single-input (force torque) – multiple-output (SIMO) mechanical system, the matrix of machine load power distribution was determined, with its components being the powers $\overline{GN}_{ik}$, $i \neq k$ (i – vibration measurement point, k – torque measurement point), which are complex quantities. The procedure of decomposition into singular values (SVD) of spectral power density matrix was made for dynamic load powers of the rolling press.

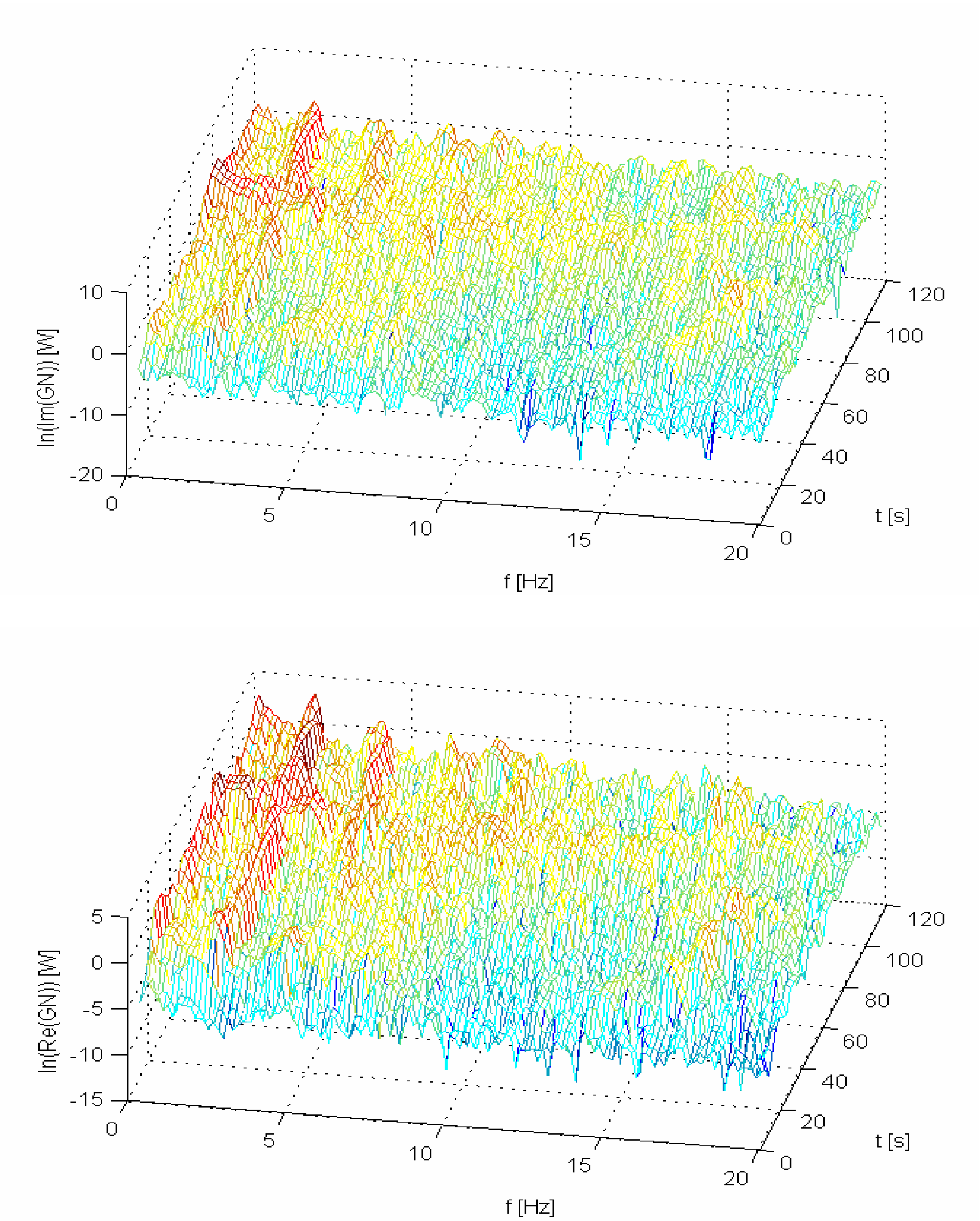

Figure. 1. Comparison of power spectral density of rigidity and inertia force powers. (upper figure) and damping force powers (lower figure),1x(hay silage)

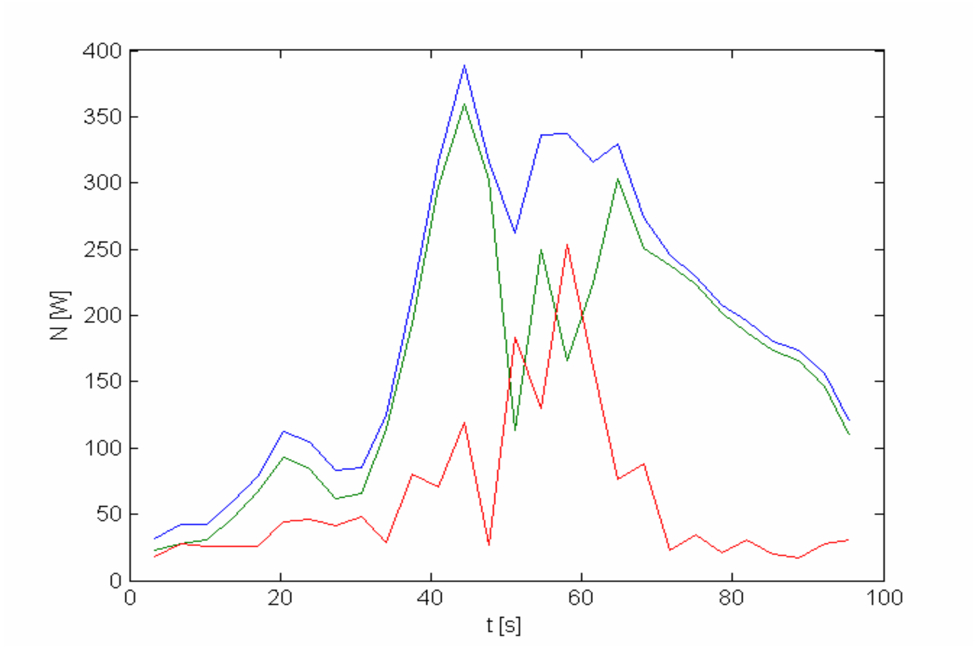

Figure. 2. Amplitude characteristics of press dynamic load (module, imaginary part – green, real part – red)

As a result of decomposition into singular values of the matrix $\overline{\mathrm{GN}}_{ik}$ performed for specific frequencies ω_k:

$$\mathrm{SVD}\left[\mathrm{G}\overline{\mathrm{N}}(\omega_k)\right] = \mathrm{SVD}\begin{bmatrix} \overline{\mathrm{GN}}(\omega_k)_{11} & \overline{\mathrm{GN}}(\omega_k)_{12} & \dots & \overline{\mathrm{GN}}(\omega_k)_{1n} \\ \overline{\mathrm{GN}}(\omega_k)_{21} & \overline{\mathrm{GN}}(\omega_k)_{22} & \dots & \overline{\mathrm{GN}}(\omega_k)_{2n} \\ \overline{\mathrm{GN}}(\omega_k)_{r1} & \overline{\mathrm{GN}}(\omega_k)_{r2} & \dots & \overline{\mathrm{GN}}(\omega_k)_{rn} \end{bmatrix} = \mathrm{U}\begin{Bmatrix} \sigma(\omega_k)_1 & 0 & \dots & 0 \\ 0 & \sigma(\omega_k)_2 & \dots & 0 \\ 0 & 0 & \dots & \sigma(\omega_k)_{\max(r,n)} \end{Bmatrix}\mathrm{V} \quad (2)$$

dominating singular values are obtained $\sigma(\omega_k)_1$.

The same method can be used to specify decomposition into singular values of the matrix $\overline{\mathrm{GN}}_{ik}$ which includes as its elements real or imaginary parts of the matrix of power density of the power.

$$\mathrm{SVD}\left[\mathrm{Im}(\mathrm{G}\overline{\mathrm{N}}(\omega_k))\right] = \mathrm{U}\begin{Bmatrix} \sigma_{\mathrm{Im}}(\omega_k)_1 & 0 & \dots & 0 \\ 0 & \sigma_{\mathrm{Im}}(\omega_k)_2 & \dots & 0 \\ 0 & 0 & \dots & \sigma_{\mathrm{Im}}(\omega_k)_{\max(r,n)} \end{Bmatrix}\mathrm{V}$$

$$\mathrm{SVD}\left[\mathrm{Re}(\mathrm{G}\overline{\mathrm{N}}(\omega_k))\right] = \mathrm{U}\begin{Bmatrix} \sigma_{\mathrm{Re}}(\omega_k)_1 & 0 & \dots & 0 \\ 0 & \sigma_{\mathrm{Re}}(\omega_k)_2 & \dots & 0 \\ 0 & 0 & \dots & \sigma_{\mathrm{Re}}(\omega_k)_{\max(r,n)} \end{Bmatrix}\mathrm{V} \quad (3)$$

The obtained decompositions bring a complete, synthetic image of dynamic loads on the machine. Dominating singular spectra σ_{Re} can be considered as estimates of dissipated power, while σ_{Im} can be treated as estimates of the powers of rigidity and inertia forces.

Specific dominating power spectra were determined for the dynamic load power of the machine and its real and imaginary parts.

During machine operation, the highest values of dynamic load power appear in low frequency bands: 0.5 - 2 Hz, 5 – 6.5 Hz, 11 – 12 Hz. Along with the increase of dynamic load powers, interrelations between the power of dynamic rigidity forces and damping forces change.

4.2 Energetic characteristics of dynamic loads describing the process of structural degradation in a wood chipping machine

Based on a complete matrix of spectral characteristics, amplitude power estimates were determined for dynamic loads in a wood chipping machine (table 1).

Table 1. Dynamic load power amplitudes for a wood chipping machine **[W]**

No. of measurement point	**Idling**		**Wood diameter:**					
			35 mm		**70 mm**		**120 mm**	
	real	imag	real	imag	real	imag	real	imag
1	2,1	2,7	3,1	1,4	10,7	7,7	257,8	308,3
2	2,0	3,1	4,9	2,3	9,7	11,9	208,5	208,1
3	1,7	2,3	3,6	1,9	5,8	11,0	299,0	327,8
4	2,1	2,8	3,5	1,6	11,2	7,6	372,6	254,0
5	2,1	2,9	5,2	2,5	12,0	12,0	367,6	325,6
6	2,0	3,1	6,3	2,8	17,5	17,7	4383,3	6774,7
7	1,8	2,7	6,8	6,4	90,6	63,2	4203,2	7100,9
8	2,7	3,0	5,2	5,1	28,3	21,7	3717,9	7375,5
9	4,3	6,5	10,5	8,3	26,7	32,7	1056,0	840,3
10	3,6	4,4	7,1	3,4	22,8	16,1	522,3	689,7
11	2,2	3,0	5,1	2,3	13,1	17,7	1004,3	1521,7
12	2,4	4,4	6,6	2,8	10,3	17,1	19,3	18,8
13	2,7	3,4	4,5	3,2	12,2	10,7	6,5	6,6
14	2,3	3,2	5,6	3,3	11,5	12,7	54,9	55,7

Dynamic loads in a wood chipping machine are of impulse character. The structure of the machine is compact. In the spectral characteristics of load power, there are no components showing particular intensity. However, the values of dynamic load powers of specific structural nodes of the machine vary.

Dynamic inertance was determined in individual points of the machine. Linear properties of the machine structure were found in a broad frequency range and large range of amplitudes.

5. CONCLUSIONS

1. In order to assess the dynamic condition of a machine, it is required to know dissipated power (real parts of dynamic load powers) and separate the powers of inertia forces and dynamic rigidity forces (imaginary parts of dynamic load powers). The method is applied in research into energy dissipation and structural changes in mechanical objects.
2. Information about the technical condition of an object can be obtained from energetic characteristics of power spectral density of dynamic load powers and amplitude estimates represented in the synthetic form for dynamic rigidity force powers and damping force powers, which change along the evolving process of their degradation. When analysing 3D diagrams of power spectral density for force powers in the function of frequency and the function of time, changes (maxima) in the run of these functions can be noticed.
3. Spectral characteristics of dynamic load powers were determined for the press used for pressing various materials. The synthesis of spectral load characteristics was obtained through decomposition of characteristics matrices into singular values, which provided the estimates of dominating spectra of power spectral density of dynamic load powers in the press.

   Energetic characteristics of dynamic loads describing the process of structural degradation in a wood chipping machine are of impulse character. Linear properties of the machine structure were found in a broad frequency range and large range of amplitudes.

REFERENCES

[1] C. Cempel, "Models of Systems for Energy Process in Theory and System Engineering". *Promotion to Doctor Honoris Causa of the Szczecin University of Technology*. 1995.

[2] H. Kaźmierczak, "Analysis of Power Distribution of Dynamic Loads in Mechanical Systems". *Wydawnictwo Politechniki Poznańskiej*, Papers 363, 2001, Poznań.

[3] H. Kaźmierczak, "Dynamic Load Power Distribution in Mechanical Systems", Issues of Machine Operations Z. 3(127) vol. 36, 2001, Radom.

[4] H. Kaźmierczak,. "Energetic Description of the Destruction Process of Machine Structural Nodes", in *Machine Dynamics Problem*, Vol. 27, No 3, 113-123, 2003, Warszawa.

[5] H. Kaźmierczak, T. Pawłowski, C. Cempel, „Energy Flow Analysis of Vibration Loads of Machines", *Eleventh International Congress on Sound and Vibration* (ICSV 11), 2004, St. Petersburg.

[6] H. Kaźmierczak,. "Energetic Characteristics of Fatigue Durability of a Machine", in *Teoria Maszyn i Mechanizmów* vol. II, Polski Komitet Teorii Maszyn i Mechanizmów at KBM PAN, 2004, AGH Kraków.

[7] H. Kaźmierczak, "Energetic Analysis of Technical Condition of Machines", in *Inżynieria Diagnostyki Maszyn*, Instytut Techn. Eksploatacji, 2004, Warszawa, Bydgoszcz, Radom.

[8] H. Kaźmierczak, J. Kromulski, C. Cempel, R. Barczewski, „Energetic Description of the steel concrete composite beam" in *New Materials and Systems for Pre-stressed Concrete Structures*, 2005, Radom.

[9] H. Kaźmierczak, J. Kromulski, T. Pawłowski, „Energetic Characteristics of Trailer Degradation", *Diagnostyka* vol.33, PTDT at Wydział Nauk Technicznych PAN, 2005.

[10] H. Kaźmierczak,., J. Kromulski, C. Cempel, R. Barczewski, „Energetic Description of the Destruction Process of Steel Concrete Structures, COST Action 534 New Materials and Systems for Pre-stressed Concrete Structures, Workshop of COST on NTD Assessment and New Systems in Pre-stressed Concrete Structures, 2005, Radom.

[11] H. Kaźmierczak,. T. Pawłowski, J. Kromulski, R. Barczewski, „Vibration characteristics of the technical degradation process of an object", *13 International Congress on Sound and Vibration*, 2–6 July, 2006, Vienna.

[12] H. Kaźmierczak,. „Energetic characteristics of dynamic loads on a machine unit", in *Teoria Maszyn i Mechanizmów*, Polski Komitet Teorii Maszyn i Mechanizmów at KBM PAN, 2006, Zielona Góra.

[13] H. Kaźmierczak, „Energetic characteristics of system degradation", *Diagnostyka* vol.38, PTDT at Wydział Nauk Technicznych PAN, 2006.

[14] H. Kaźmierczak, J. Kromulski, "Energetic characteristics of structure degradation in a mechanical object", *XXXIII National Symposium on MACHINE DIAGNOSTICS*, 2006, Węgierska Górka.