Deterministic and Probability Analysis of Paper Machine Vibration Impact to the Structure Safety and Human Comfort

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Abstract. *This paper describes the probability and sensitivity analysis of the concrete frame and paper machine interaction. On the base of the experimental results, the calculation FEM model was verified. The uncertainties of the loads level, the material properties and other influences following the inaccuracy of the calculated model and numerical methods were considered in the approximation method RSM.*

Keywords

ANSYS, Machine Vibration, Probability, Safety, Human Comfort, FEM, RSM.

1. Introduction

The paper presents solutions of the problems that have arisen after installing a new technology of a higher-end paper machine into the original factory building. After the start of the operation, there were problems with the interaction of the machine with the load-bearing structure, which threatened both the load-bearing structure and the impact on the human comfort of the person working in the hall.

Due to the problems of interaction between the paper machine and the existing industrial hall structure, it was necessary to experimentally measure these effects and to modify a computational model and analyse the effect of interaction on the structures and human comfort of the workers, and to propose of the reconstruction of the existing structure or design of dampers to maximally eliminate the effects of machine and structure interaction.

On base of the problems with the paper machine and hall structure interaction, it was necessary to analyse the effect of the dynamic interaction by the experimental measurements of the vibrations of the stool-technology-hall system to eliminate the adverse resonant effects of the proposed technology on the hall structure. The reconstruction work involved the exchange of part of the technology in the screen, winding and upstream part of the machine.

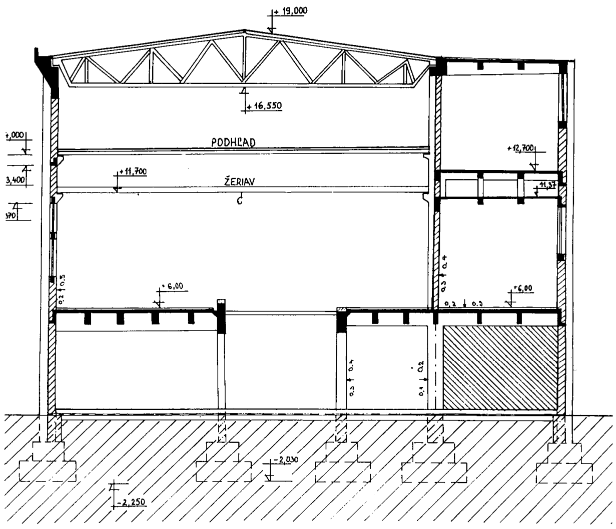


Fig. 1: The section of the hall frame

The supporting structure of the hall consists of a reinforced concrete frame with a masonry walls. The individual floors of one hall section are reinforced with monolithic concrete plates with grid beams. The section of the reinforced concrete columns is 45/70 cm, the frame modulus is 9-4.5-4.5-6 m in frame plane and 6 m in perpendicular direction. The machine is placed at level 5.65 m. The bottom/top levels of the columns are at -0.25/18.23 m.

The following experimental and numerical analyses were carried out based on the need to review the concept of construction work on the given object:

- Experimental testing and evaluation of the dynamic interaction of the interaction system in all holding states of the paper machine,
- Numerical Analysis of the Problem of Interaction with the Present State Given Designed Machine Parameters.

As part of the numerical analysis, it was necessary to make a complete dynamic calculation of the spatial system, a modal analysis considering the interaction of the substructure-construction-technology [6-21, 28].

2. Design criteria of the structure reliability and human comfort

From the point of view of the Eurocode recommendations [5, 7, 13, 14] and national standards [24, 25], the designer should assess the effects of machine vibrations on the following effects:

- Impact of machine vibrations on building construction
- Influence of vibrations on man and on operation (mechanical, acoustic and optical)
- Impact of Machine Vibration on Machinery (manufacturer's recommendations and limitations)
- Based on the assessment of all impacts, the following criteria [7] are required:
- Criteria for the limit state of load-bearing capacity and instability of structures [5]
- Physiological criteria [25]
- Operational performance criteria (manufacturer's requirements)

In standard [25], the categorization of structures in terms of criteria for the 1st limit state is made based on values of effective oscillation velocity depending on the reliability classes and the significance of the object. Reinforced concrete structures of industrial buildings are classified in the resistance class *E* and the consequention classes *II*.

The requirements of the design of the human comfort and its protection are defined in the standards [25]. The standards define the criterions of the human comforts from the point of the interrupted and common vibrations.

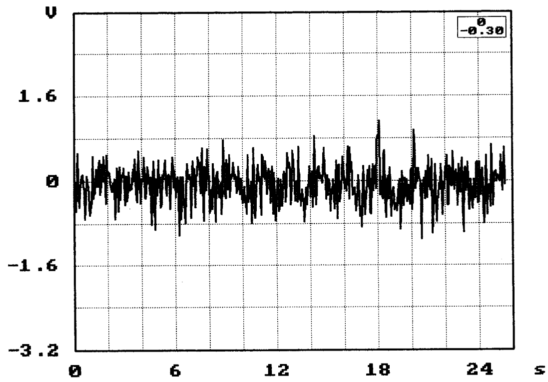
The criterions of the quality of the vibration influences on the human comfort are not defined only in dependency on the intensity of vibrations but from the point of view of the functionality of the building rooms and the frequency and the time of the vibration action to the human. The type of the diagrams defined in standard [25] is used to the design of the influence the vibrations on human comfort.

3. Experimental modal analysis

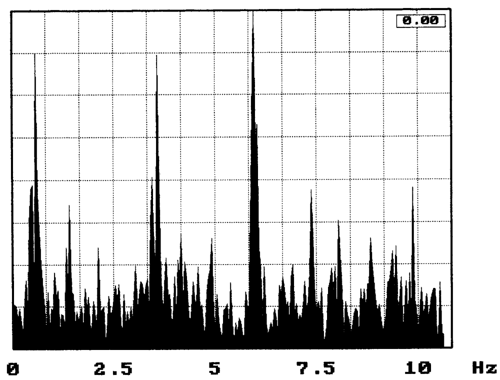
In order to check the dynamic properties of the structure, it was necessary to measure the vibration response in the critical places [2-4, 18, 19]. A measuring system was used, the basic element of which was the piezoelectric accelerometer KD 35 and KD 22. Their signal was led to the integrating RFT 00OLS amplifier and after amplification to both the Tesla EMM 140 and the TRACE 860SA digital oscilloscope.

Vibration acceleration rates and values were measured at five locations [4]:

- on the main beam by the operator at the same site,
- on the outside of the building,
- on the floor in the center of the monolithic slab,
- on the operator's side,
- on the floor at the control floor,
- on the floor.



a) Accelerations at floor in time



b) Acceleration spectrum at floor

Fig. 2: Evaluation of the experimental acceleration record on the bottom of cylinder drive motor [4]

From the number of vibration spectra evaluated, it was possible to see the different frequencies of individual frequencies from place to location. The dominant eigen frequencies of the building structure were determined.

4. Numerical analysis

Within the numerical analysis of the soil-structure-technology interaction system, it was necessary to prove that the stool under the paper machine meets the criteria set by the manufacturer and, on the other hand, the load-bearing structure can transfer the dynamic load caused by the technology [1, 6, 11-15, 18, 19, 23, 26-28].

The spatial discretization of the structure was performed by the one-dimensional elements LINK8 and BEAM4 and two-dimensional shell elements SHELL43. Three calcu-lation models were constructed - Fram1, Fram2 and Fram3 (Fig.3). The Fram1 model responds to the original design and original load, Fram2 original design and new load, and Fram3 reinforced construction and new load. The total calculation model consists of 686 nodes and 1216 elements with six degrees of freedom. The pillars are fixed on the foundation pad.

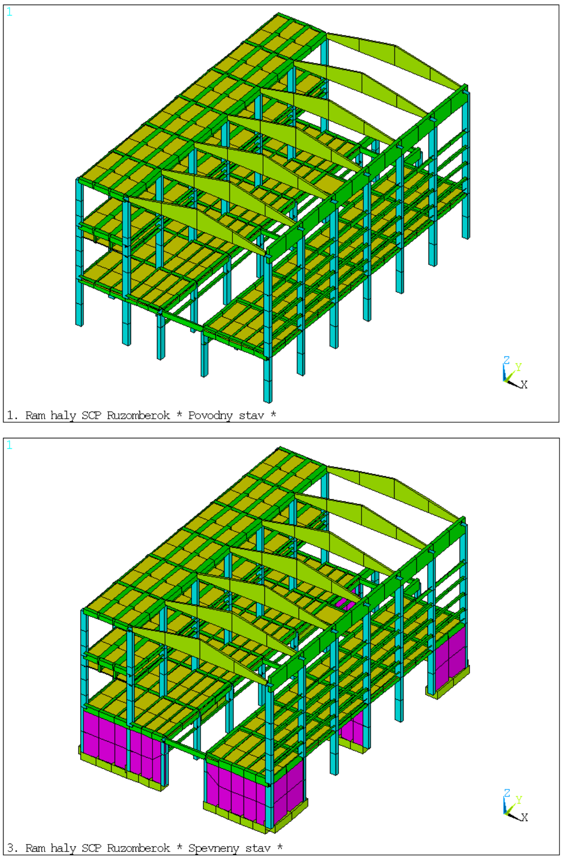


Fig. 3: Calculation frame models - Fram1, 2 and Fram3

The dynamic calculation of the system consisted of:

- modal analysis
- dynamic analysis of the response to harmonic oscillation

$$\mathbf{M\ddot{u}}+\mathbf{C\dot{u}}+\mathbf{Ku}=\mathbf{F}(t) \tag{1}$$

where **M, C, K** are the mass, damping and stiffness matrices, $\ddot{\mathbf{u}}, \dot{\mathbf{u}}$ and $\mathbf{u}$ are vectors of nodal acceleration, velocities and displacements. In the case of harmonic exciting forces, we express the vector of the displacements and excitation forces as follows

$$\mathbf{u}=\mathbf{u}_1+i\mathbf{u}_2 e^{i\Omega t} \quad \text{and} \quad \mathbf{F}=\mathbf{F}_1+i\mathbf{F}_2 e^{i\Omega t} \tag{2}$$

where $\mathbf{u}_1$ (or $\mathbf{u}_2$) is the real (or imaginary) component of the vector of displacements and $\mathbf{F}_1$ (or $\mathbf{F}_2$) is the real (or imaginary) component of the excitation vector of forces. After we put relationships (2) into (1) we get dynamic equations (1) in the form of complex equations

$$\left(\mathbf{K}-\Omega^2\mathbf{M}+i\Omega\mathbf{C}\right)\left(\mathbf{u}_1+i\mathbf{u}_2\right)=\mathbf{F}_1+i\mathbf{F}_2 \tag{3}$$

The columns of frames are jointed with the pad footing embedded on the subsoil consisting of a gravel with a velocity of shear waves v_s = 700 m/s. The pad footing has been modelled by LINK8 weave elements, whose rigidity and damping characteristics were determined by [6], where ρ is the specific gravity of the soil, B, L are ground plan dimensions of the base foot, β_x, β_z, β_ψ are coefficients dependent on the shape of the foot according to [6].

$$k_x=2(1+\nu)G\beta_x\sqrt{BL}\,,\quad k_z=\beta_z\sqrt{BL}\,G/(1-\nu)\,,$$
$$k_\psi=\beta_\psi BL^2\,G/(1-\nu)\,,\quad k_t=16GR^3/3\,,$$
$$R=\sqrt[4]{BL\left(B^2+L^2\right)/6\pi}\,, \tag{4}$$
$$c_x=0{,}576k_xR\sqrt{\rho/G}\,,\quad c_z=0{,}85k_zR\sqrt{\rho/G}\,,$$
$$c_\psi=0.3k_\psi R\sqrt{\rho/G}/\left(1+B_\psi\right),\quad c_t=\sqrt{k_t i_t}/\left[1+2I_k/\left(\rho^5R\right)\right]$$
,

where k_x, k_y, k_z are longitudinal stiffness, k_ψ, k_t are rotational and torsional stiffness, c_x, c_y, c_z are longitudinal damping, c_ψ, c_t are rotational and torsional damping.

Due to the significant influence of the stiffness of the soil on the dynamic characteristics of the structure of the building [1, 11-15, 18], it is advisable to consider three low-medium-high values, based on the median value and the values of the lower and upper quantum, assuming the normal distribution [22]. The upper and lower value k_p defined for normal distribution of the stiffness of the soil are expressed in the form [7]:

$$k_p=k_m.\left(1\pm u_p.k_w\right) \tag{5}$$

where k_p is the quotient of the stiffness of the subsoil (for probability p = 0.05 and p = 0.95), k_m is the mean stiffness of the subsoil, k_w is the value of the soil stiffness variation ($k_w = k$ at s/km), u_p is the normalized value of the quotient, quantity. If you consider 24% of the standard deviation and the normal distribution, it is a factor of 0.6 / 1 / 1.4 (Low / Medium / High).

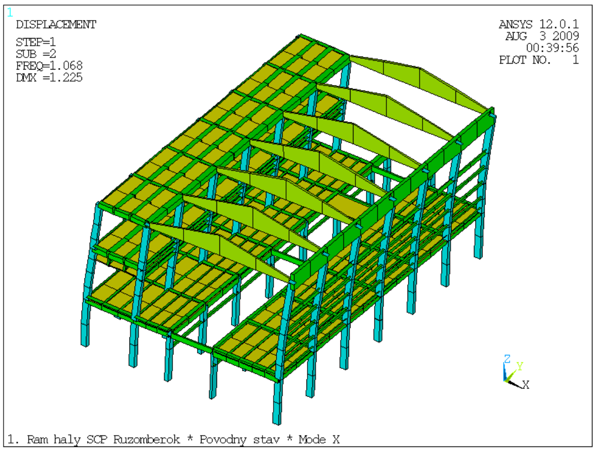
The influence of soil stiffness on the frequency characteristics of the structure is shown in Tab. 1. Modal analysis was performed using the Lanczos iteration method based on Cholean method of factorization of mass and stiffness matrix. The mode shape for two of the critical frequencies can be seen in Fig. 4.

Tab. 1: Comparison of the influence of the soil stiffness to significant modes

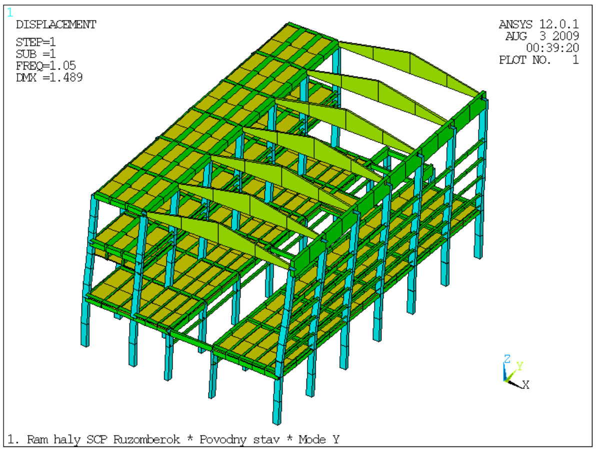
Model		Mode in direct. X/Y/Z	
Frame	Soil type	Frequency [Hz]	Relative masses [%]
F1 and F2	L	1.03/1.04/5.05	58.51/58.35/44.82
	M	1.07/1.05/5.82	23.68/57.58/88.29
	H	1.09/1.06/6.2	58.50/57.34/49.56
F3	L	1.15/4.24/6.14	55.01/41.81/46.10
	M	1.28/5.21/6.60	34.50/29.32/60.61
	H	1.29/6.21/10.35	33.54/26.85/33.34

*) Note - L / M / H- lower / middle / upper stiffness of the soil

By comparing the values of the deciding eigen frequencies of the structure, the rigidity of the soil significantly affects the values of the frequencies in the horizontal direction. There is a jump of decisive frequencies at the low and medium stiffness of the soil. It should be noted that the other frequencies are closer to frequencies than to the original design.



a) The decisive shape of oscillation in X direction



b) The decisive shape of oscillation in Y direction

Fig. 4: Principal modes of the original structure

At a paper speed of 450 m/min, the rotation speed of the 1.6 Hz drying rollers is a state that has existed for 10 years and does not resonate [4]. Increasing the speed of paper movement to 700 m/min represents an increase in the rotation speed of cylinders to 2.5 Hz. In the range of 1.6 - 2.5 Hz, we find our own frequencies, which have a small share in the total effective weight of the system. We have dealt with the direct method of solving the complex equations of the harmonic load by the oscillation of the paper machine.

5. Loads and load combinations

The load and load combination in the case of deterministic as well as probabilistic assessment of the limit state of load capacity and serviceability of the structure are considered according to STN ENV 1991-1 [7] as follows:

A) Deterministic combinations

$$\sum_{j\geq 1} \gamma_{Gj.\inf} G_{kj.\inf} + \gamma_{Q.1} Q_{k.1} \tag{6}$$

$$\sum_{j\geq 1} \gamma_{Gj.\sup} G_{kj.\sup} + \gamma_{Q.1} Q_{k.1}$$

B) Probabilistic combinations

$$\sum_{j\geq 1} g_{\text{var}} G_{kj} + q_{\text{var}} Q_k \tag{7}$$

where G_{kj} is the characteristic value of constant loads (for the adverse effect $G_{kj.inf}$ and the beneficial effect of $G_{kj.sup}$), Q_{k1} - the characteristic value of the predominant variable load, γ_{Gj} - the partial coefficient for permanent load, γ_{Q1} - the partial coefficient for variable load 1, g_{var} , q_{var} - variable coefficients in the form of a standard histogram. The partial coefficient values in relations (6) and (7) are considered for the limit state of capacity and usability as follows [7]:

- limit state of load capacity
  ($\gamma_{Gj.inf} = 0.9$; $\gamma_{Gj.sup} = 1.1$; $\gamma_{Q.1} = 1.5$)
- limit state of serviceability
  ($\gamma_{Gj.inf} = 1.0$; $\gamma_{Gj.sup} = 1.0$; $\gamma_{Q.1} = 1.0$)

6. Uncertainties of input parameters

The variability of the vertical stiffness of the soil (Table 2) is defined by the characteristic $k_{z.k}$ stiffness obtained from the in-situ measurements and the variable coefficient of $k_{z.var}$.

Tab. 2: Probability model of input parameters

Type	Quantities	Charact. values	Variabil. paramet.	Histo-gram*)	Mean μ	Dev. σ
Soil	Stiffness	$k_{z,k}$	$k_{z.var}$	N	1	0.24
Material	Modulus	E_k	e_{var}	LN	1	0.05
Load	Dead	G_k	g_{var}	N	1	0.10
	Live	Q_k	q_{var}	G	1	0.35
	Amplitude	F_k	f_{var}	LN	1	0.10
	Frequency	Fr_k	fr_{var}	N	1	0.10
Model	Action	θ_E	Te_{var}	N	1	0.05
	Resistance	θ_R	Tr_{var}	N	1	0.05

*) N - Normal, LN - Lognormal, G - Gama

The stiffness of the structure is determined by the characteristic value of the Young's E_k module and the coefficient of variability e_{var}. The load is characterized by the values G_k, F_k, $F_{r.k}$ and variable factors g_{var}, f_{var} and $f_{r.var}$ (Tab. 2). The uncertainty of the computational model is considered by the variable model coefficients and the variable coefficient of load effect for Gaussian normal distribution. The probabilistic analysis was performed under the ANSYS system by the approximate RSM method using the CCD [14] experimental design method for 79 simulations. From the results of the probabilistic analysis models "*Fram1*" and "*Fram2*" show, that the dominant frequency is changing in the direction *X* (from 0.83 Hz in 1.41 Hz), *Y* (from 0.83 Hz to 1.37 Hz) and *Z* (from 4.19 Hz-7.48 Hz). From the results of the probabilistic analysis models "*Fram1*" and "*Fram2*" show that the dominant frequency is changing in the direction *X* (from 0.83 Hz in 1.41 Hz), *Y* (since in the case of paved construction of "*Fram3*" is the dominant frequency of the change in the direction of *X* (from 1.02 HZ-1.68 Hz), *Y* (3.86 Hz to 6.63 Hz) and *Z* (from 4.99 Hz to 8.35 Hz). These ranges of frequencies can have a significant impact on the response of harmonic oscillation the paper machine.

7. Comparison of deterministic and probabilistic analysis

Comparison of deterministic and probabilistic solution of the safety and reliability of the design of building is documented in Table 3. From the table see a comparison of the horizontal and vertical displacements for the three calculation models, the structures (Fram1, Fram2 and Fram3) obtained from the deterministic analysis (for three variations of the soil stiffness) and from the probabilistic analysis. The values of maximum displacements, velocities and acceleration at the level of the foundations does not exceed the limit values given in the standards STN 73 0032 and DIN 4150. Maximum vertical displacements of the structure indicate a possibility of failures in accordance with the criteria STN 730036 (Tab.1).

Tab. 3: A comparison of the maximum peak of the displacements at top of frames

Model	Analysis	Direction *)	Displacement [mm]			
			Probability of exceedance			Dev.
			5%	50%	95%	σ
Fram1	Determin.	H	2.80	3.06	3.29	-
		V	7.26	8.88	12.72	-
	Stochastic	H	1.21	4.80	8.42	2.19
		V	4.88	8.59	12.31	2.26
Fram2	Determin.	H	2.02	2.22	2.85	-
		V	7.81	9.74	14.63	-
	Stochastic	H	1.73	2.63	3.52	0.54
		V	4.93	9.39	13.85	2.72
Fram3	Determin.	H	0.91	0.91	1.02	-
		V	4.37	5.06	8.08	-
	Stochastic	H	1.01	1.38	1.76	0.23
		V	3.72	5.85	7.98	1.30

*) H – horizontal, V - vertical

From the point of the human comfort the peak velocity at floor level were calculated on original and reinforced frame and compared with the graph No.8 in nomogram of standard [25]. The limit value is equal 2.7 mm/s for frequency 2.5 Hz. The peak velocities in the horizontal and vertical directions were equal $v_{x.peak}$ = 5.65 mm/s > 2.7 mm/s and $v_{z.peak}$=5.59 mm/s > 2.7 mm/s at original frame (Frame2). After reinforcement of the frame by system of the concrete walls the peak velocities in the horizontal and vertical directions were equal $v_{x.peak}$ = 1.4 mm/s < 2.7 mm/s and $v_{z.peak}$ = 0.44 mm/s < 2.7 mm/s (Frame3) calculated deterministic. In the case of the probabilistic analysis the peak velocity for the probability of exceedance 95% in the horizontal and vertical directions were equal $v_{x.peak}$ = 2.41 mm/s < 2.7 mm/s and $v_{z.peak}$ = 0.43 mm/s < 2.7 mm/s (Frame3).

8. Conclusions

The reliability analysis of the safety and reliability of the hall structure with the paper machine, depending on the variability of the stiffness of the sub-soil, mechanical characteristics of materials, and the operation of the machine, as well as the uncertainty of the model and the resistance were presented in this paper. The analytical model was tested by experimental measurement on a real structure. The methodology of the probabilistic analysis of the soil-structure-machine interactions was presented on the practical problem in the paper factory after changing the technology. After reinforcement of the frame with the concrete walls, the values of the displacements were reduced by 30%. The probabilistic analysis gives to the engineer-designers a more complex information's about the interaction of the system soil-structure-machine as deterministic.

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