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DYNAMIC CHARACTERISTICS OF A NEW MACHINE FOR FATIGUE TESTING OF RAILWAY AXLES – PART 2

DYNAMICKÉ CHARAKTERISTIKY NOVÉHO STROJE PRO TESTOVÁNÍ ÚNAVY ŽELEZNIČNÍCH NÁPRAV – ČÁST 2

Abstract

There were done some proposal calculations for a new testing machine. This new testing machine is determined for a dynamic fatigue testing of railway axles. The railway axles are subjected to bending and rotation (centrifugal effects). For the right proposition of a new machine is very important to know the basic dynamic characteristics of whole system. These dynamic characteristics are solved via FEM (MSC.Marc/Mentat software) in combination with SBRA (Simulation-Based Reliability Assessment) Method (probabilistic Monte Carlo approach, Anthill and Python software). The proposed dimensions and springs of a new machine for fatigue testing of railway axles were used for manufacturing. Application of the SBRA method connected with FEM in these areas is a new and innovative trend in mechanics. This paper is continuation of former work (i.e. easier deterministic approach) already presented in this journal in 2007.

Abstrakt

Byly provedeny návrhové výpočty nového zkušebního stroje. Tento nový zkušební stroj je určen pro dynamické únavové testy železničních náprav. Železniční nápravy jsou namáhány ohybem a rotací (odstředivé efekty). Pro správný návrh nového stroje je velmi důležité znát základní dynamické charakteristiky celého systému. Tyto dynamické charakteristiky jsou řešeny MKP (MSC.Marc/Mentat software) v kombinaci s metodou SBRA (Simulation-Based Reliability Assessment - pravděpodobnostní přístup Monte Carlo, Anthill a Python software). Navržené rozměry a pružiny nového stroje pro únavové testování železničních náprav byly použity pro výrobu. Aplikace metody SBRA spojené s MKP v této úloze, je novým a inovativním trendem v mechanice. Tento článek je následujícím pokračováním dřívější práce (tj. jednoduchý deterministický přístup) již prezentované v tomto časopise v r. 2007.

1 INTRODUCTION

Let us consider the Simulation-Based Reliability Assessment (SBRA) Method, see [5], [6], [7], [9] and [10], a probabilistic direct Monte Carlo approach, in which all inputs are given by bounded histograms. Bounded histograms include the real variability of the variables. Using SBRA method, the probability of failure (i.e. the probability of undesirable situation) is obtained mainly by analyzing the reliability function RF = RV – S, see Fig. 1. Where RV is the reference (allowable) value and S is a variable representing the load effect combination. The probability of failure is the probability that S exceeds RV (i.e. $P(\mathrm{RF}\leq 0)$). The probability of failure is a relative value depending on the definition of RV and it usually does not reflect an absolute value of the risk of failure.

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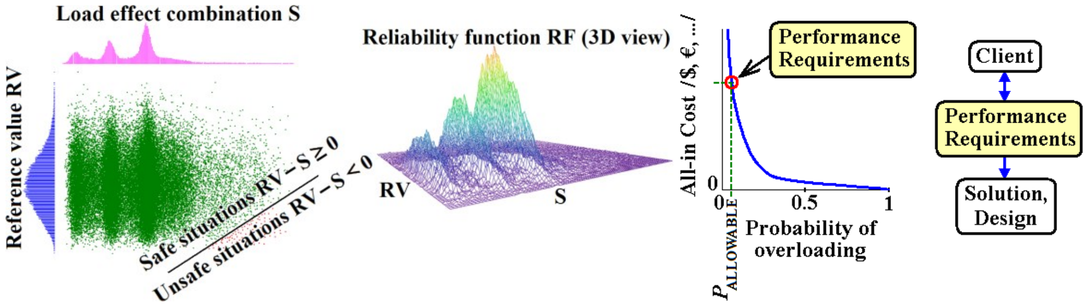


Fig. 1 Reliability function RF (SBRA Method) and definition of the acceptable probability of overloading.

This paper focuses on the practical application of the probabilistic approach (i.e. SBRA Method) applied in the area of machine design (i.e. designing of the new massive machine for fatigue testing of railway axles). Today's European standards define material quality of railway axles including requirements for chemical composition, material behaviour, stress-strain calculations in individual points of axle-cross-sections, fatigue testing and its evaluation, see standards [1], [2] and [3]. The determination of a fatigue limit for railway axles loaded by composed bending and rotation is described in [3].

Hence, there were done some proposal calculations for a new testing machine. This new testing machine is determined for a fatigue testing of railway axles, see Fig. 2. The railway axles are subjected to bending and rotation (centrifugal effects). The fatigue tests for railway axles which are made in actual size are very important for verifications of all calculations and acceptations of new designs. In the past in the Czech Republic, only SVÚM in Prague provided fatigue tests using Sinco-TEC rezonator. Hence a new kind of rezonator was designed in the BONATRANS GROUP a.s. (Bohumín, Czech Republic), see Fig. 2. The shaft exciter is described (loaded) via centrifugal force Fo /N/.

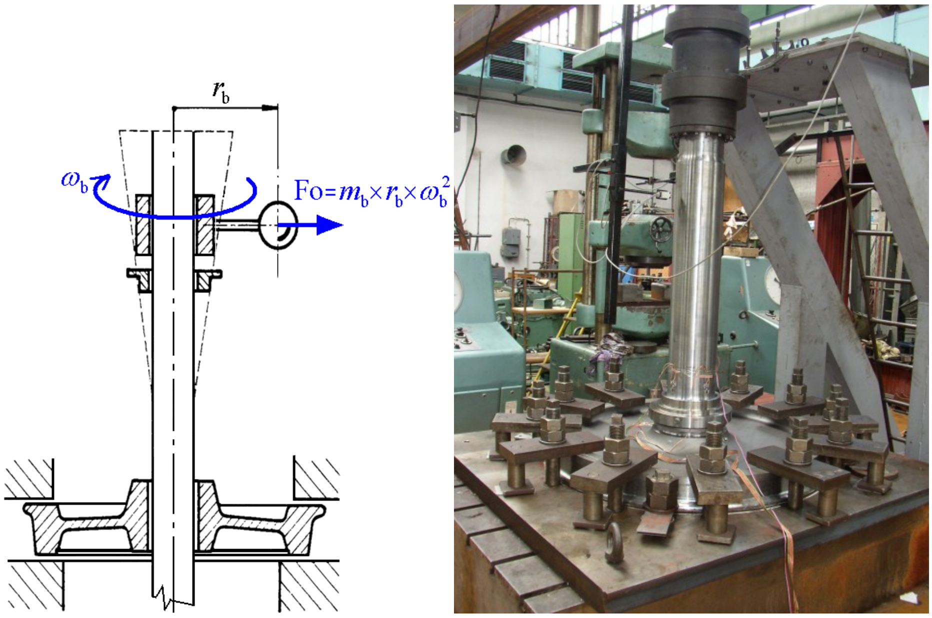


Fig. 2 Fatigue testing of railway axles (principles and measurements).

2 NUMERICAL MODELLING

For the right proposition of a new machine for fatigue testing of railway axles (resonator) is very important to know the basic dynamic characteristics of whole system. These dynamic characteristics are solved via FEM (MSC.Marc/Mentat software, see Fig. 3). The base (botton part) of the testing machine in made of concrete and the upper part (i.e. railway axle) is made of steel, see Fig. 3. Two versions of testing machines with different dimensions and with 12 or 16 springs were solved, see Fig. 4. The springs are described by non-linear stiffnesses in radial and axial directions. Damping propperties of concrete and steel (elastic materials) was described by Rayleigh material damping. For both versions of FE models were solved modal analyses via Lanczos method and transient analyses (starting of machines to the steady-state conditions).

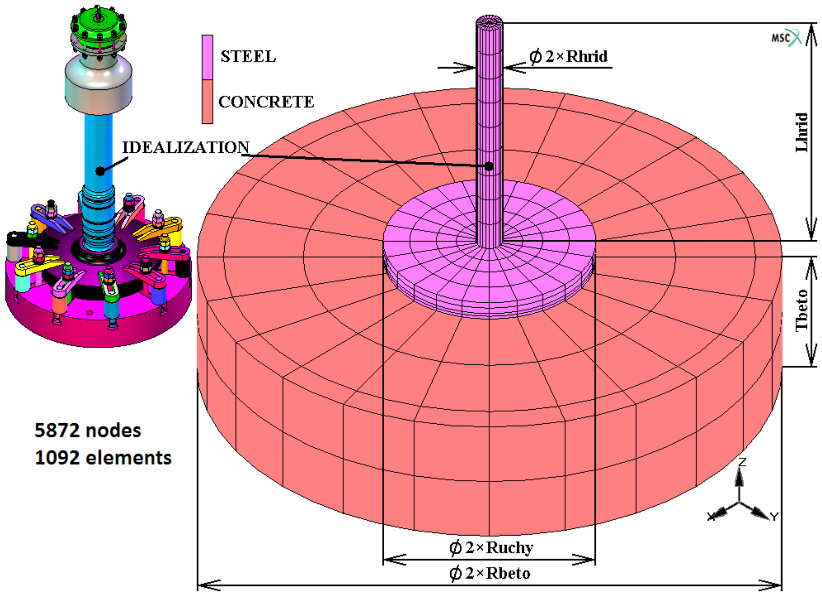


Fig. 3 Fatigue testing of railway axles (Finite Element Method).

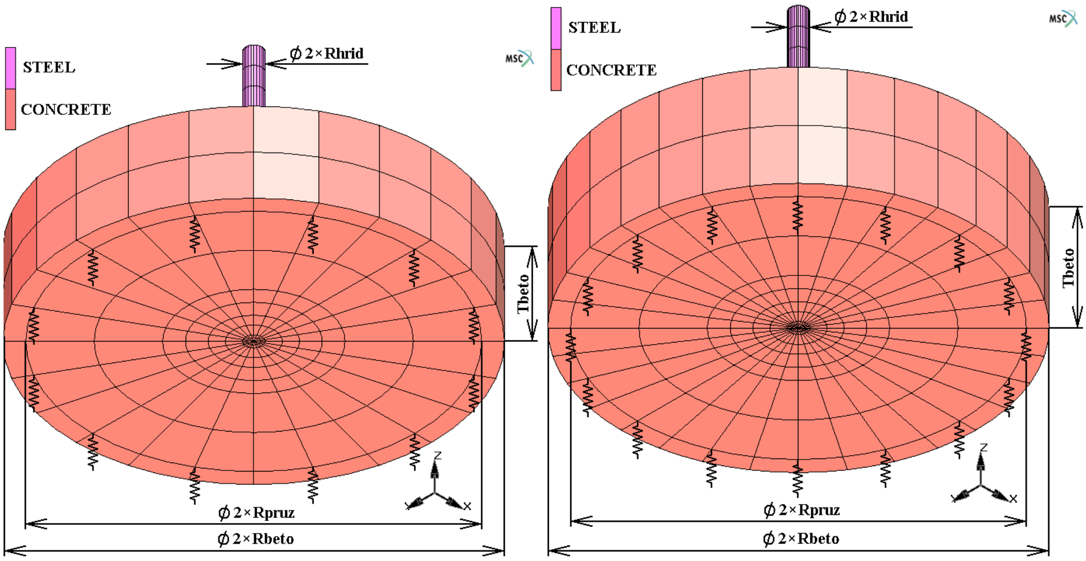


Fig. 4 The FE models with 12 and 16 springs.

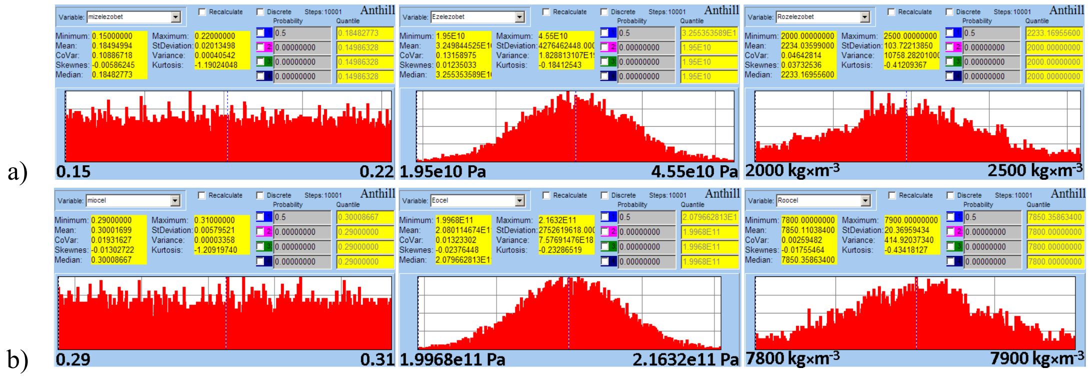
3 DETERMINISTIC APPROACH (FEM)

A deterministic approach (i.e. all types of loading, dimensions and material parameters etc. are constant) provides an older but simple way to simulate mechanical systems. However, a deterministic approach cannot truly include the variability of all inputs (i.e. variability of material properties of the ore), because nature and the world are stochastic. Solution of the ore disintegration process via deterministic approach (i.e. basic simple solution) is shown in reference [4]. Deterministic approach is applied in [8], [9] and [11] too.

4 PROBABILISTIC APPROACH (FEM + SBRA METHOD)

From the nature is known, that material properties and dimensions of the testing machine, including railway axles, have stochastic variability. Hence, the stochastic approach (i.e. SBRA Method in combination with FEM is applied). MSC.Marc/Mentat and Anthill software was used in modelling this problem, see references [4] and [5].

Examples of 6 probabilistic inputs (i.e. histograms) for material properties (i.e. Poisson's ratio /1/, modulus of elasticity /Pa/, and density /kg×m^{-3}) are shown in Fig. 5a (concrete) and in Fig. 5b (steel).



Variable: mizelezobet
☐ Recalculate ☐ Discrete Steps: 10001
Minimum: 0.15000000 Maximum: 0.22000000
Mean: 0.18494994 StDeviation: 0.02013498
CoVar: 0.10886718 Variance: 0.00040542
Skewnes: -0.00586245 Kurtosis: -1.19024048
Median: 0.18482773
☐ 1: 0.5 0.18482773
☐ 2: 0.00000000 0.14986328
☐ 3: 0.00000000 0.14986328
☐ 4: 0.00000000 0.14986328

Variable: Ezelezobet
☐ Recalculate ☐ Discrete Steps: 10001
Minimum: 1.95E10 Maximum: 4.55E10
Mean: 3.249844525E1 StDeviation: 4276462448.00
CoVar: 0.13158975 Variance: 1.828813107E1
Skewnes: 0.01235033 Kurtosis: -0.18412543
Median: 3.255353589E1
☐ 1: 0.5 3.255353589E1
☐ 2: 0.00000000 1.95E10
☐ 3: 0.00000000 1.95E10
☐ 4: 0.00000000 1.95E10

Variable: Rozelezobet
☐ Recalculate ☐ Discrete Steps: 10001
Minimum: 2000.00000000 Maximum: 2500.00000000
Mean: 2234.03599000 StDeviation: 103.72213850
CoVar: 0.04642814 Variance: 10758.2820100
Skewnes: 0.03732536 Kurtosis: -0.41209367
Median: 2233.16955600
☐ 1: 0.5 2233.16955600
☐ 2: 0.00000000 2000.00000000
☐ 3: 0.00000000 2000.00000000
☐ 4: 0.00000000 2000.00000000

Variable: miocel
☐ Recalculate ☐ Discrete Steps: 10001
Minimum: 0.29000000 Maximum: 0.31000000
Mean: 0.30001699 StDeviation: 0.00579521
CoVar: 0.01931627 Variance: 0.00003358
Skewnes: -0.01302722 Kurtosis: -1.20919740
Median: 0.30008667
☐ 1: 0.5 0.30008667
☐ 2: 0.00000000 0.29000000
☐ 3: 0.00000000 0.29000000
☐ 4: 0.00000000 0.29000000

Variable: Eocel
☐ Recalculate ☐ Discrete Steps: 10001
Minimum: 1.9968E11 Maximum: 2.1632E11
Mean: 2.080114674E1 StDeviation: 2752619618.00
CoVar: 0.01323302 Variance: 7.57691476E18
Skewnes: -0.02376448 Kurtosis: -0.23286519
Median: 2.079662813E1
☐ 1: 0.5 2.079662813E1
☐ 2: 0.00000000 1.9968E11
☐ 3: 0.00000000 1.9968E11
☐ 4: 0.00000000 1.9968E11

Variable: Roocel
☐ Recalculate ☐ Discrete Steps: 10001
Minimum: 7800.00000000 Maximum: 7900.00000000
Mean: 7850.11038400 StDeviation: 20.36959434
CoVar: 0.00259482 Variance: 414.92037340
Skewnes: -0.01755464 Kurtosis: -0.43418127
Median: 7850.35863400
☐ 1: 0.5 7850.35863400
☐ 2: 0.00000000 7800.00000000
☐ 3: 0.00000000 7800.00000000
☐ 4: 0.00000000 7800.00000000

Fig. 5 Probabilistic inputs – a) histograms of concrete properties (Poisson's ratio, modulus of elasticity, density) – b) histograms of steel properties (Poisson's ratio, modulus of elasticity, density).

From the results of modal analyses is possible to calculate the critical frequencies. For example, the dominant frequency is the $7^{\text{th.}} \equiv 8^{\text{th.}}$ critical frequency $f_{\mathrm{CR}_{7,8}} \in (32.643; 34.122)\,\mathrm{Hz}$, see histogram and distribution function in Fig. 6.

From the results of transient analyses, for example see Fig. 7, is possible to calculate the radial displacement u_{RAD} /m/ in the end of shaft. These displacements depend on frequence $\mathrm{n_b}$ /Hz/ of exciter (i.e. $u_{\mathrm{RAD}} = f(\mathrm{n_b})$), see Fig. 8a (results of 1 Monte Carlo simulation) and Fig. 8b (results of 10001 Monte Carlo simulations).

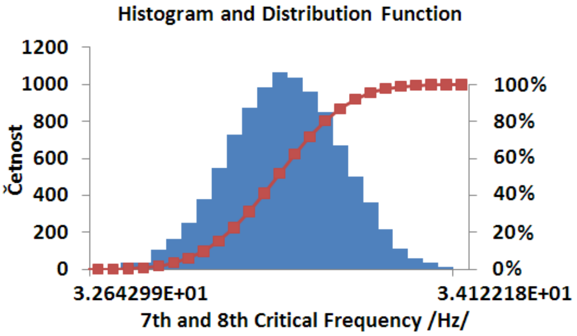


Fig. 6 Probabilistic outputs - Histogram and distribution function for $7^{\text{th}} \equiv 8^{\text{th.}}$ critical frequency $f_{\mathrm{CR}_{7,8}} \in (32.643; 34.122)\,\mathrm{Hz}$.

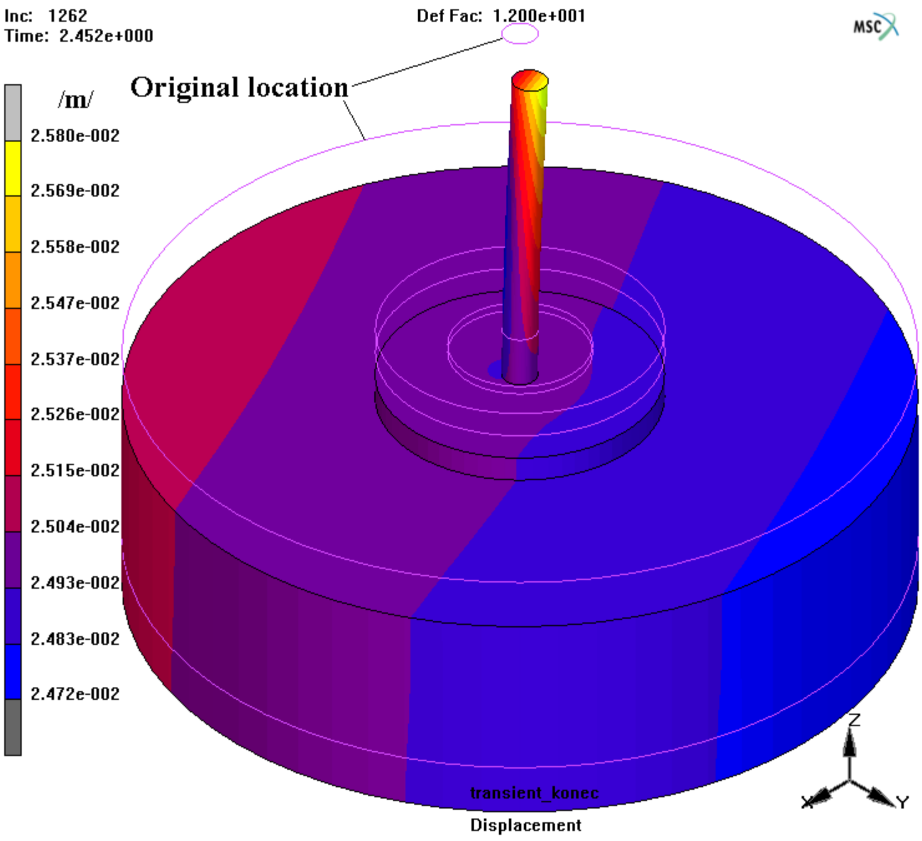
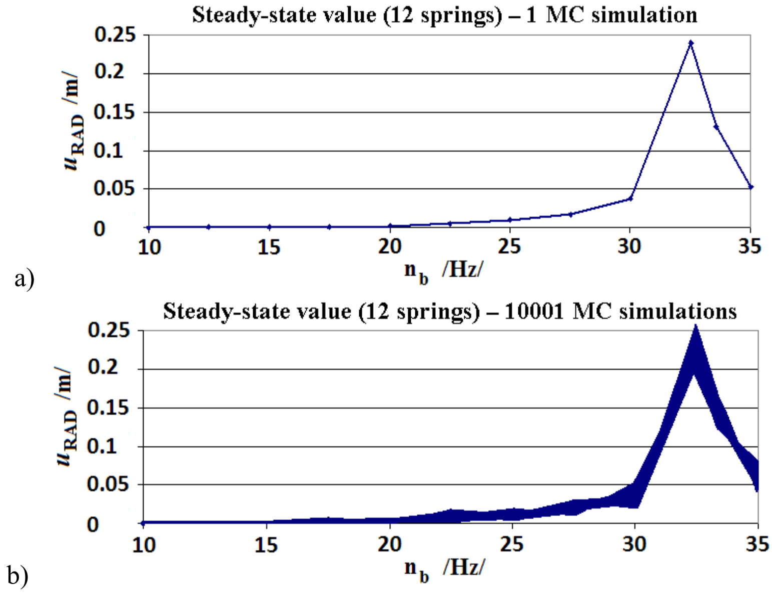


Fig. 7 Total displacement in time $t = 2.452\ \mathrm{s}$ (transient analysis, 16 springs, excitation $\mathrm{n_b} = 25\ \mathrm{Hz}$).



a)

b)

Fig. 8 Probabilistic outputs - dependence of displacement u_{RAD} on excitation frequence $\mathrm{n_b}$ (transient analyses, 12 springs).

Finally, the maximal bending stress σ_o /MPa/ can be calculated in the shaft (i.e. $\sigma_o = f(\mathrm{n_b})$), see Fig. 9. The higher values of bending stresses (higher than yield limit) are calculated with accepted mistakes because the plasticity of materials was not enabled. But all the basic dynamic characteristics are calculated correctly.

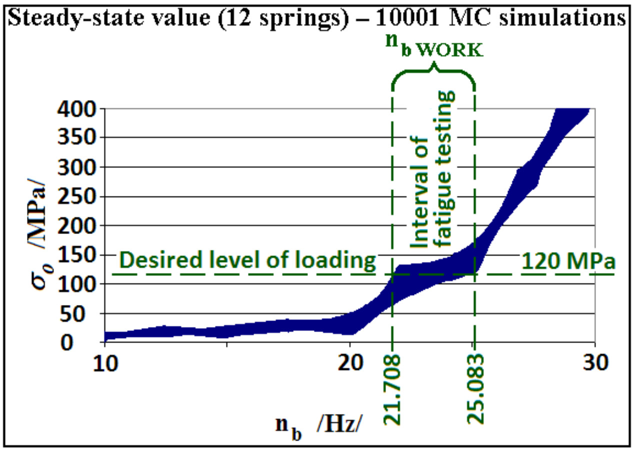


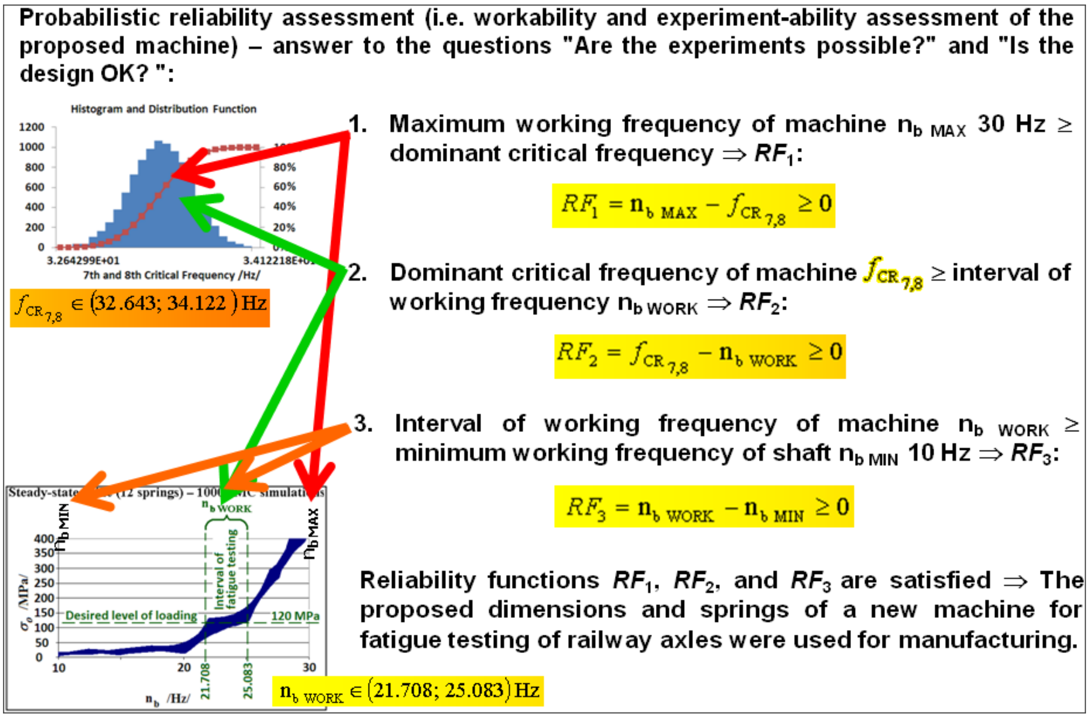
Fig. 9 Probabilistic outputs - dependence of maximal bending stress σ_o on excitation frequency $\mathrm{n_b}$.

5 CONCLUSION

This paper combines the SBRA (Simulation Based Reliability Assessment) Method and FEM as a suitable tool for simulating the complicated tasks of mechanics.

The dynamic characteristics were solved via FEM in combination with SBRA Method. From the acquired results, see chapter 4, and required conditions of experiments, see [4], [5] and [10], is known that the maximal bending stress $\sigma_{o\mathrm{MAX}} = 120\,\mathrm{MPa}$. Hence, the interval of working frequency $\mathrm{n_{b\,WORK}} \in (21.708; 25.083)\,\mathrm{Hz}$ can be determined, see Fig. 9. This interval represents the variability of working mode of the proposed machine for fatigue testing of railway axles, where minimum of working frequency is $21.708\,\mathrm{Hz}$ and maximum is $25.083\,\mathrm{Hz}$. Hence, it is evident that the workability of the proposed machine is in the interval from cca 1875571 to 2167171 loading cycles/day. Therefore, this machine is suitable to perform fatigue tests of railway axles in a few days (i.e. the proposed design is suitable for doing low-cycle and high-cycle fatigue tests).

The reliability functions RF_1 to RF_3 are presented in Fig. 10. For more information see reference [5]. Application of the SBRA method connected with FEM in these areas is a new and innovative trend in mechanics. The proposed dimensions and springs of a new machine for fatigue testing of railway axles were used for manufacturing.



Probabilistic reliability assessment (i.e. workability and experiment-ability assessment of the proposed machine) – answer to the questions "Are the experiments possible?" and "Is the design OK? ":

1. **Maximum working frequency of machine $n_{b\ MAX}$ 30 Hz ≥ dominant critical frequency ⇒ RF_1:**

$$RF_1 = n_{b\ MAX} - f_{CR_{7,8}} \geq 0$$

2. **Dominant critical frequency of machine $f_{CR_{7,8}}$ ≥ interval of working frequency $n_{b\ WORK}$ ⇒ RF_2:**

$$RF_2 = f_{CR_{7,8}} - n_{b\ WORK} \geq 0$$

3. **Interval of working frequency of machine $n_{b\ WORK}$ ≥ minimum working frequency of shaft $n_{b\ MIN}$ 10 Hz ⇒ RF_3:**

$$RF_3 = n_{b\ WORK} - n_{b\ MIN} \geq 0$$

Reliability functions RF_1, RF_2, and RF_3 are satisfied ⇒ The proposed dimensions and springs of a new machine for fatigue testing of railway axles were used for manufacturing.

$$f_{CR_{7,8}} \in (32.643; 34.122)\ \mathrm{Hz}$$

$$n_{b\ WORK} \in (21.708; 25.083)\ \mathrm{Hz}$$

Fig. 10 Probabilistic reliability assessment of the new design of the machine for fatigue testing of railway axles.

ACKNOWLEDGEMENT

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