Monitoring Residual Fatigue Lives of Steam Turbine Blades

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Abstract: The paper deals with a postprocessing of output files from Blade Tip Timing – BTT systems. A brief description of the main algorithm steps is presented. Finally, a new RFLB system (Residual Fatigue Life of Blades) is announced, which enables operators being informed of the state of blades from a measured wheel during operation.

Keywords: Turbine Blades; Fatigue; Residual Life; BTT System; RFLB System.

1 Introduction

Producers of all machines strive to ensure the highest reliability of their products. The bigger machine, the higher efforts are devoted to this aim. This is the reason, why producers of big turbosets fit out their products with a plenty of measuring equipments for getting actual information on their state.

One of the most exposed parts of turbines are blades. They are working at rather complicated operational conditions like high radial stress from centrifugal forces and extreme velocity of wet steam turbulent flow exciting them to vibrations accompanied by alternating stresses. Dynamic stresses may initiate material damage, which results in a crack propagation, when cumulated. Since this phenomenon may end in total breakdown of a blade followed by an unplanned shutdown of the machine, producers of turbomachines arm their products with systems, which are able to monitor blades at critical places of the machine. Monitoring systems used for that purpose are denoted as BTT – Blade Tip Timing systems, because they are based on time measurement of blade tips, when passing sensors. The measured data, series of times, are processed off-line into natural frequencies of blades and histograms of position magnitudes.

2 Residual Fatigue Life of Blades

An appendage to BTT, the RFLB system, has been developed at Research and Testing Institute Plzeň in the framework of project "Center of Research and Experimental Development of Reliable Energy Production" sponsored by the Technological Agency of the Czech Republic [1]. The RFLB system processes files generated by BTT systems to get estimates of fatigue lives of all blades from a measured wheel [2]. The goal is reached in several steps:

- at first, samples of time signals from all blades are stripped of overflow, centered, divided into parts, if too long, and Fourier transformed getting thus aliased Fourier spectra,
- aliased resonant frequencies are adjoined to the real ones based on their FEM calculations and experimental verifications in the Campbell machine,
- frequency bands close to resonances in aliased Fourier spectra are moved to right positions in the reconstructed Fourier spectra, and remaining noise parts of the spectra are spread uniformly all over the real frequency interval,
- the inverse Fourier transform of the reconstructed Fourier spectra yields reconstructed signals of blade tip movements, extremes of which create time series for an additional analysis,
- the rainflow method is applied for decomposition of extreme time series into full- and half-cycles,
- a damaging stress [3] and corresponding relative damage increments are evaluated from stress tensors at critical places at each blade,
- the damage increments are cumulated giving thus information on the most damaged blades.

2.1 Blade Tip Timing

Blade tip timing systems are based on accurate time measurements by a counter, which counts high frequency clock pulses. The current content of the counter is stored in a memory of the BTT system, when a control pulse generated in an adjoint probe (sensor) by a passing blade tip comes to the counter. The stored time series of times are irregular due to the blade vibration. The reference, one-per-revolution sensor, serves for synchronization purposes, see Fig. 1.

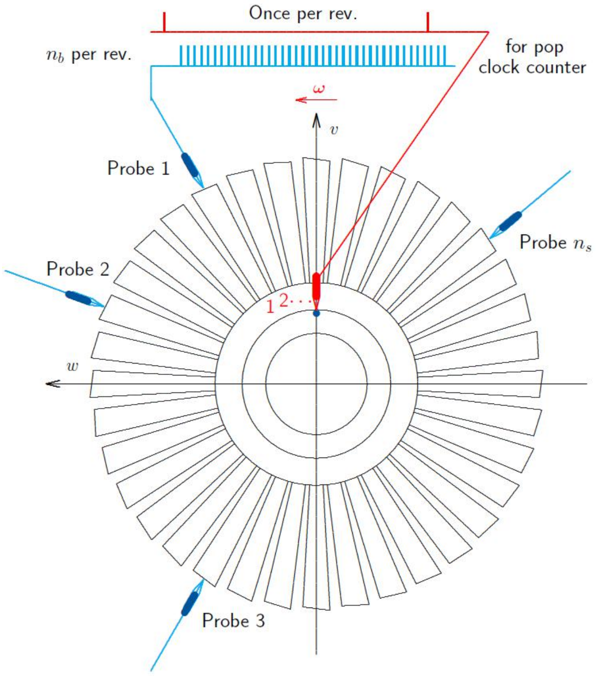

Fig. 1: Blade Tip Timing system.

2.2 Aliasing and Fourier Transform

Since natural frequencies f_n of blades are much greater than sampling frequency f_s, (of rotation), all frequencies lower than twice the sampling frequency will be aliased under Fig. 2. Only the frequencies $f_n < 2\,f_s$ remain unchanged. This is obvious from Fig. 3, where all frequency components were aliased into the interval $0 \leq |f| \leq 25\,\mathrm{Hz}$, because the speed of the bladed wheel was 3000 RPM and natural frequencies of blades were $f_n > 170\,\mathrm{Hz}$. It is known from the Shanon-Kotelnikov theorem that from such spectra the original signals can't be reconstructed.

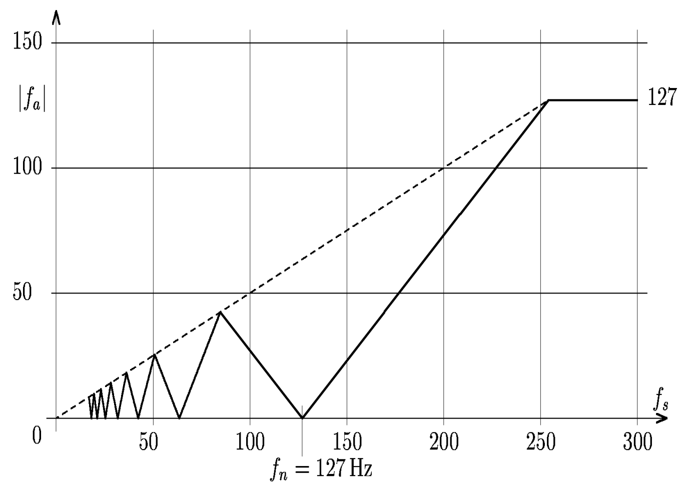

Fig. 2: Stroboscopic effect of undersampling.

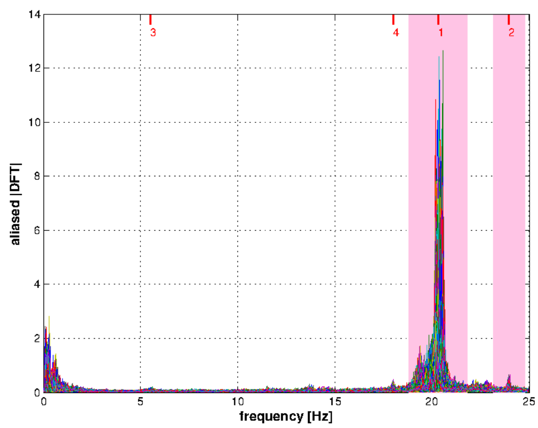

Fig. 3: Aliased Fourier spectra modules.

2.3 Reconstruction of a Blade Tip Movements

Fortunately, situation is not so hopeless as it appears. Natural frequencies f_n are calculated during the design of a machine and after that the resonant frequencies are measured in a testing bed, the Campbell machine. Both sets of frequencies can serve as additional information allowing to reconstruct the signals. The resonant frequency bands of aliased Fourier spectra are moved into real frequencies of reconstructed spectra with respect how the aliased spectra were created. The remaining parts of aliased Fourier spectra are spread over the real Fourier spectra, and then the reconstructed signals of blade tip are found by the inverse Fourier transform.

Fig. 4 presents a comparison of the measured samples of a single blade tip movement as magenta circles, and the corresponding reconstructed signal as a blue line. The figure shows the total measurement of the duration 600 [s] and then parts of 20 [s] and 0.5 [s]. Quality of the reconstruction may be assessed via coincidence of samples with a line of the reconstructed signal, which seems be very good.

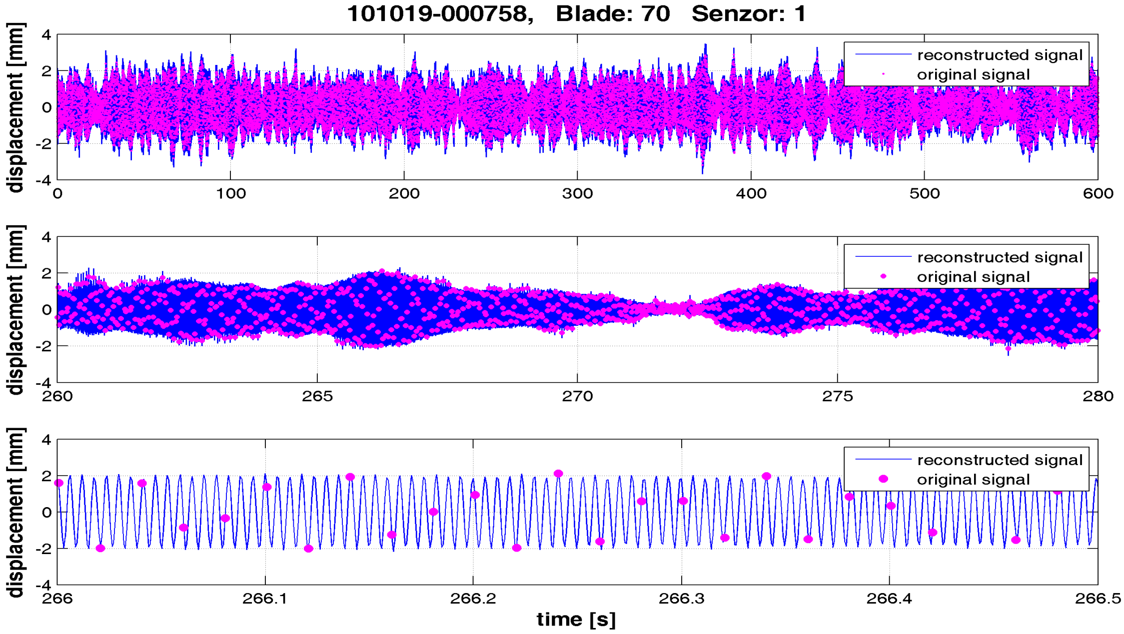

Fig. 4: A comparison of the measured samples and the reconstructed signal of a single blade tip.

2.4 Damage Estimates

As soon as the signals of blade tips are reconstructed, the processing of measured data proceeds by the evaluation of amplitudes of damaging stress [3] defined for kth cycle as $\sigma_{ak} = [\max(\sigma_{dk}) - \min(\sigma_{dk})]/2$, where μ is the Poison's number and

$$\sigma_{dk} = \Delta t_k \left[+ \sqrt{\tilde{\sigma}_x^2 + \tilde{\sigma}_y^2 + \tilde{\sigma}_z^2 - 2\mu\,(\tilde{\sigma}_x\tilde{\sigma}_y + \tilde{\sigma}_y\tilde{\sigma}_z + \tilde{\sigma}_z\tilde{\sigma}_x) + k_c^2\,(\tilde{\tau}_{yz}^2 + \tilde{\tau}_{zx}^2 + \tilde{\tau}_{xy}^2)} \right]_k, \tag{1}$$

where $k_c = \sigma_c/\tau_c \approx \sqrt{2(1+\mu)}$ and symbols with tilde are dynamic components of a stress tensor in the critical point corresponding to nth mode of vibration. Time-series of damaging stress course are decomposed into a set of full cycles and half cycles by a rain-flow procedure getting thus stress amplitudes σ_{ak} and mean stresses σ_{mk} needed for an estimation of elemental damage d_k in kth cycle by a fatigue hypothesis. The most common one is the hypothesis of Palmgren-Miner respecting an influence of σ_m on $N_{cm} = N_c(\sigma_m)$ and $\sigma_{cm} = \sigma_c(\sigma_m)$,

$$d_{k,\mathrm{PM}} = \frac{1}{N_c\,\sigma_c^w}\,\frac{\sigma_{ak}^w}{g_m\,h_m^w}\bigg|_{k,\,\sigma_{ak}>\sigma_{cm}}, \tag{2}$$

where g_m and h_m are functions of mean stress σ_m, namely $g_m = 1 - \left(\frac{\sigma_m}{R_m}\right)^2$ and $h_m = \left(1 - \frac{\sigma_m}{R_m}\right)^{k_H}$.

Elemental damages can be cumulated for all the time of machine operation in $D_{\mathrm{PM}} = \sum_{\forall\,k} d_{k,\mathrm{PM}}$. Fig. 5 displays for all blades how cumulated damage from one measurement grew in time. The damage growth is not uniform in time as is seen from Fig. 6. Residual fatigue life is a complement of a relative damage to unity.

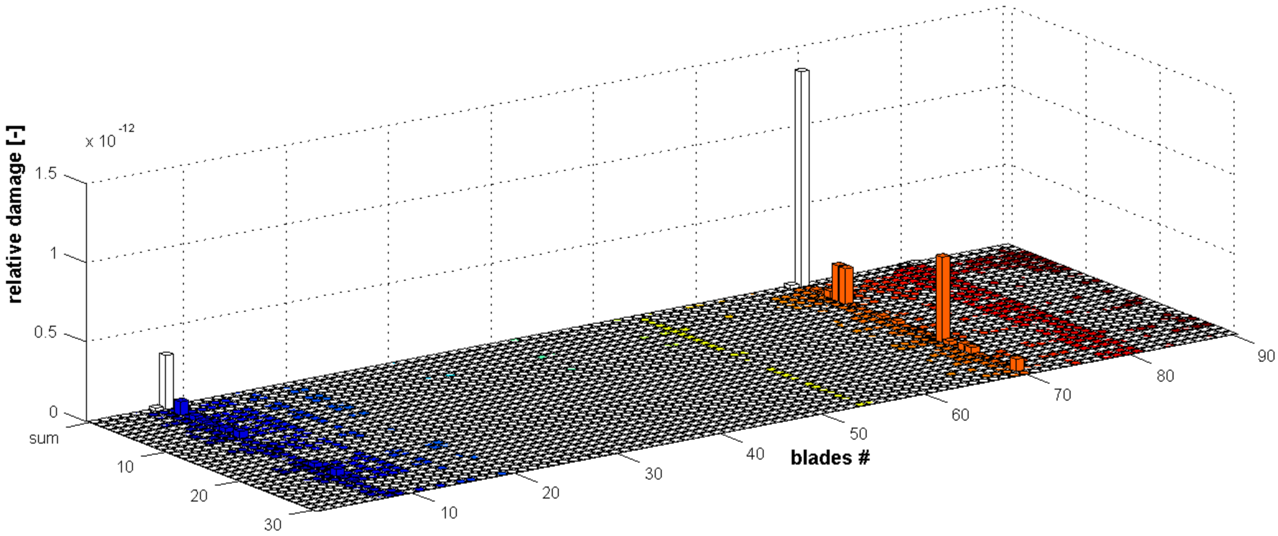

Fig. 5: Damage cumulation over all set of blades in time.

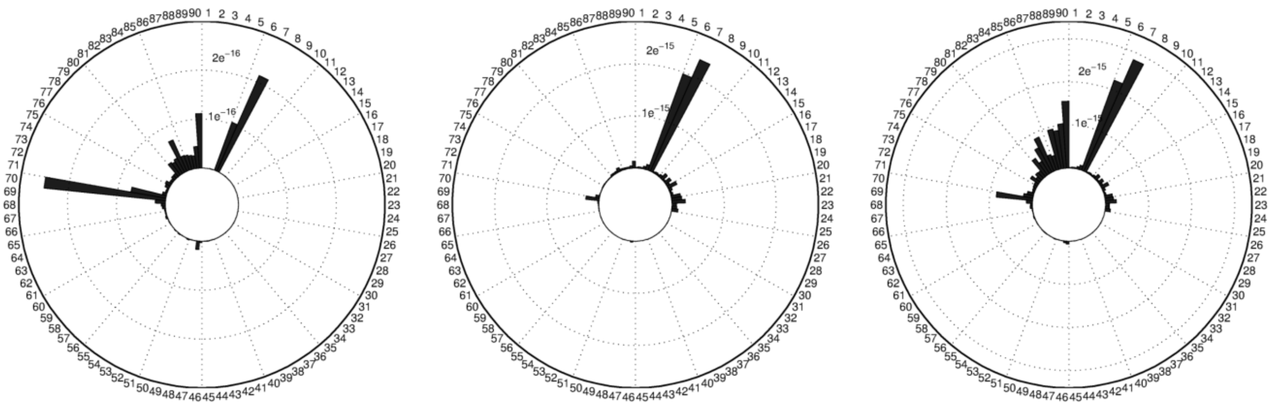

Fig. 6: Relative damage cumulation in subsequent measurements.

3 Conclusion

The paper describes the new method of predicting residual fatigue life of blades by postprocessing output files from the installed BTT systems.

Acknowledgement

The contribution has originated in the Research and Testing Institute Plzeň in the framework of works on the project “Center of Research and Experimental Development of Reliable Energy Production” sponsored by the Technological Agency of the Czech Republic.

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53rd Conference on Experimental Stress Analysis
Český Krumlov, Czech Republic, June 1–4, 2015

Analysis of Satellites Loading in Planetary Transmission

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Abstract: This paper is focused on determination of satellites loading in a planetary transmission. This kind of analysis of loading in a planetary transmission is called load sharing. For the analysis, it is used experimental analysis with used strain gauges.

Keywords: Gears; Planetary Transmission; Experimental Analysis; Strain Gauge.

1 Introduction

In this case, load sharing is monitored with tooth testing at the same time. For teeth load monitoring on gears, strain gauges are used [1]. The main reason for strain gauges measurement method was monitoring of the load across the width of the tooth. However if strain gauges are installed on the ring gear or pinion tooth, than it should be monitored by meshing with satellites. With respect to action-reaction law teeth loading from gears to satellites is assigned.

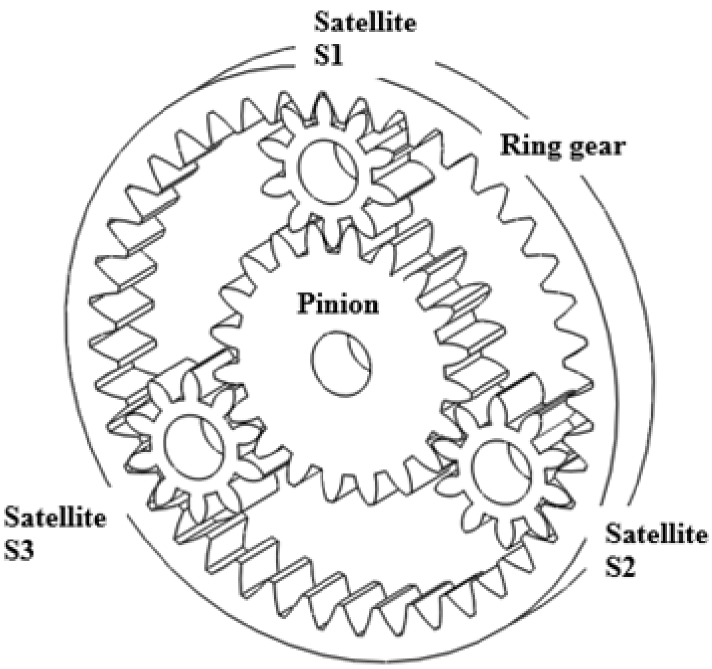

Fig. 1: Planetary transmission – 3 Satellites.

2 Measurement

Strain gauges are placed on flank face (Fig. 2) considering the meshing [2].

Measured signal from strain gauges is presented on Fig. 3. For example is given measurement with four strain gauges. In the first line there are data from all four strain gauges. In other lines there are signals from individual strain gauges which are marked as T1, T2, T3 and T4.

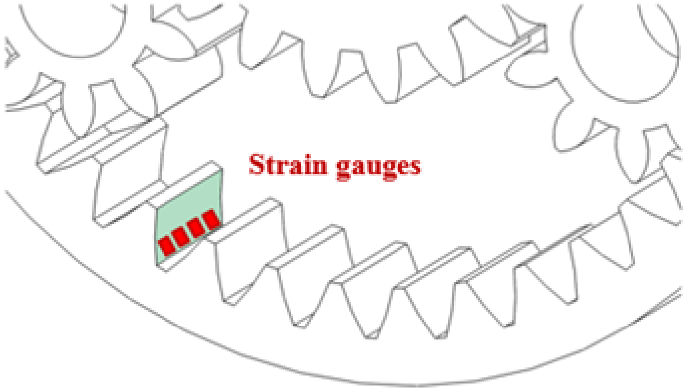

Fig. 2: Strain gauges on tooth.

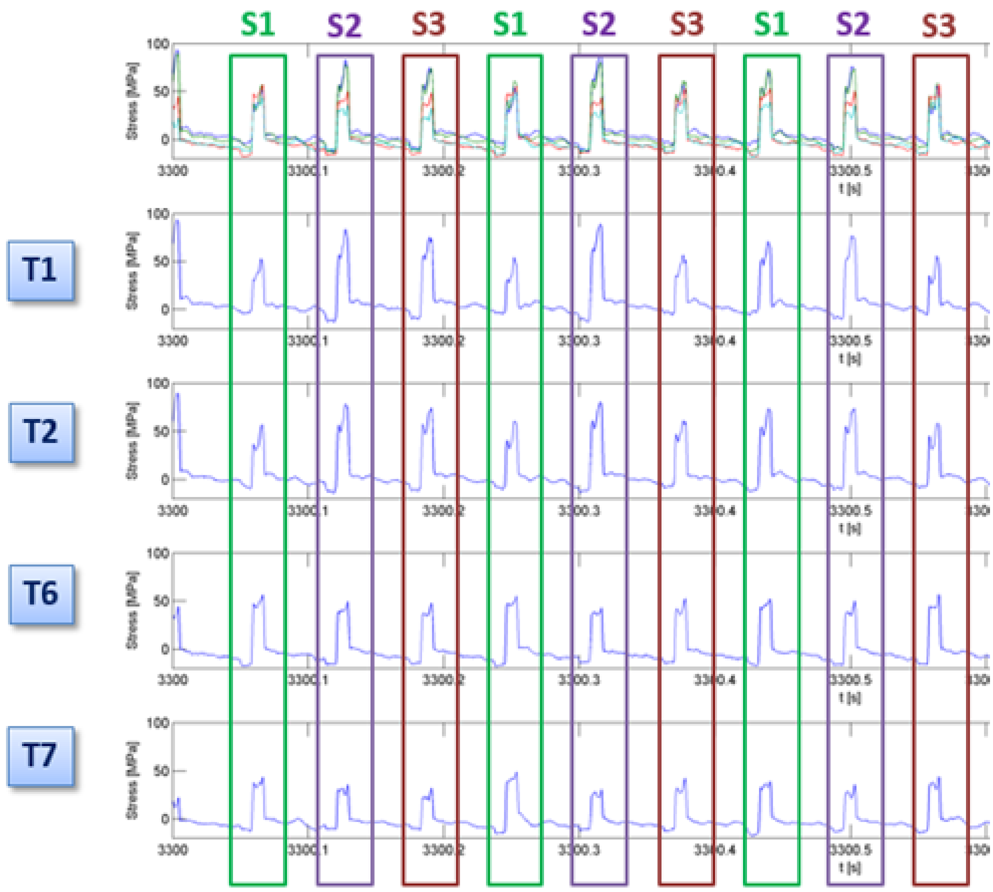

Fig. 3: Signals from strain gauges.

From this presented data, the gear mesh with individual satellites have to be identified. Relevant columns are corresponded to satellites S1, S2 and S3. Dividing of these data for satellites is very easy, because we know a gear mesh frequency. Next step, data for individual satellites are connected (Fig. 4) and between peaks time range are inserted. Thanks to this fact, general loading time behaviour corresponds with real time.

For load sharing evaluation is used average mean from strain gauges from one the tooth.

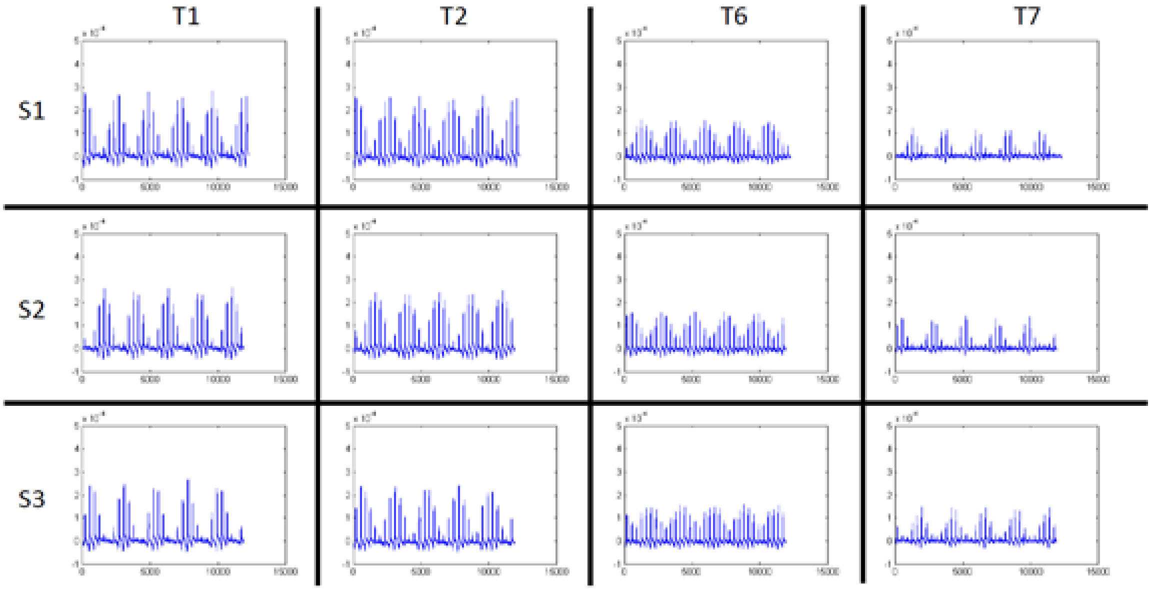

Fig. 4: Connected data of satellites.

This data arrangement enables to describe and compare the time behaviour of satellites loading (Fig. 5). That information serves to detection of potential machine defects. This loading dependence are determined from maximum of peaks of tooth loading (Fig. 6), individually for every satellites.

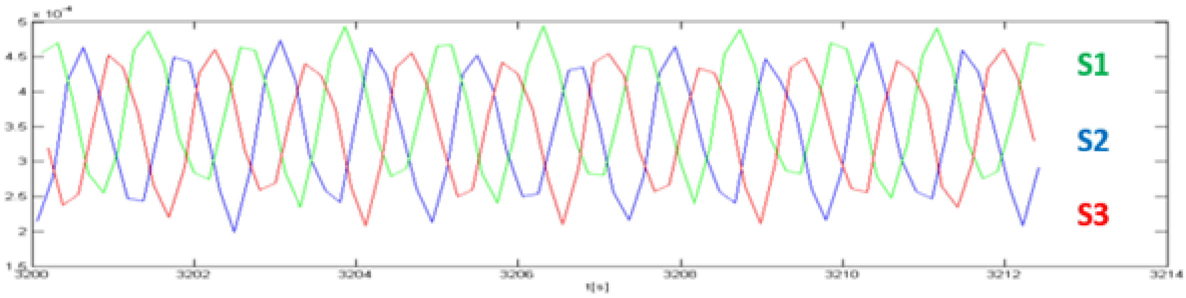

Fig. 5: Satellites loading.

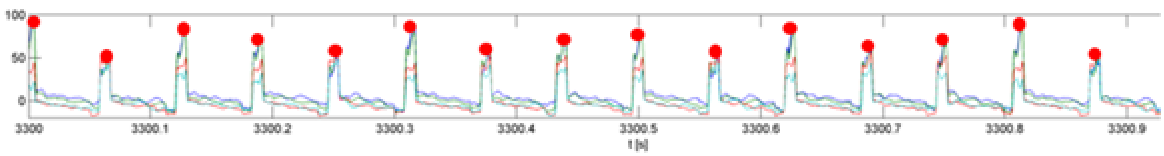

Fig. 6: Selection of peaks maximum.

3 Conclusion

Data for individual satellites and theirs comparison are output (Fig. 7). Method enables to determine non-uniform power flow, which could be effected by geometrical induced deviation, reduced stiffness or other possible transmission defect.

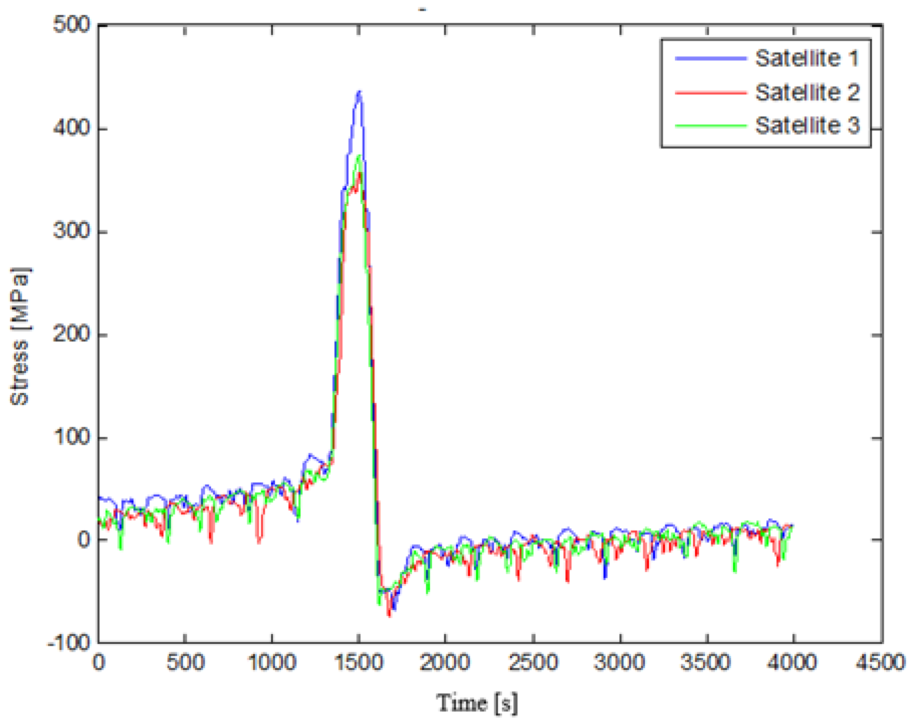

Fig. 7: Comparison of satellites loading.

That kind of measurement gives data of contacts with individual satellite. Data for individual satellites are not given at the same time. It's a case when satellites contact with the ring gear goes in ones and twos. If satellites should be measured at the same time than it is necessary to install strain gauges on more tooth. Specifically strain gauges have to be installed opposite one of the position of the satellites.

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