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AUTONOMOUS ONLINE SYSTEM FOR EVALUATING STEEL STRUCTURE DURABILITY

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Summary

The article deals with the design of equipment and its application possibilities for on-line monitoring of operational stress traverse mechanisms. By processing of load spectra it is possible to predict the remaining life in the selected areas of the construction.

Key words: measurement chain, accumulating unit, strain gauge measurement, fatigue damage

1. INTRODUCTION

Current trend in developing of new structures aims at increasing of productivity, quality, reliability and hence also durability. Structural durability is influenced by several factors; most significantly by fatigue, overload, corrosion, and wear, etc. The predominant factor that causes damage during normal operation is fatigue. Up to 90% of all structures get damaged when they are affected by fatigue. The fatigue life analysis is used to determine the time to failure under operational load. These questions are analysed by authors in the papers [1, 2, 3]. Failure occurs in the points of extreme stress. Generally, their localization by numerical methods of elasticity requires excellent knowledge of material characteristics as well as marginal conditions of location and load. Numerical analysis of the steel structure parts is performed usually by means of the experimental measurements in order to obtain time behaviour of the operational loading [4, 9].

2. DATA ACCUMULATION AND PROCESSING SYSTEM STRUCTURE

Acquiring load spectra from actual operational loads requires long-term measurements. Quantitative measurement of specified quantities made in the traditional system entails accumulation of an extremely large data file. Recording such an amount of data for multiple measurement nodes is not only technically difficult to perform, but above all it is uneconomical and it has low reliability. Measuring devices available for common applications in multiple measuring points intended for permanent use are not advantageous. For this reason, a measuring device with a microchip was specially designed to pre-process the measured signal. A measurement chain was developed to enable selected strain parameters to be tracked online based on the familiar principles of sensing the physical quantity of strain, such as resistance strain gauge. Concurrently, an online algorithm to process the measured data which could be implemented in a mobile microcomputer was developed. The whole device comprises two basic parts – a measuring and accumulating unit and a visualization computer. The measuring and accumulating unit is mounted on the selected points of the traveling track structure. It performs an on-line measurement and tracking of the selected strain parameters; their processing in real time, and archiving for the subsequent transfer to the visualization computer. Fig, 1 illustrates the simplified structure of the whole system.

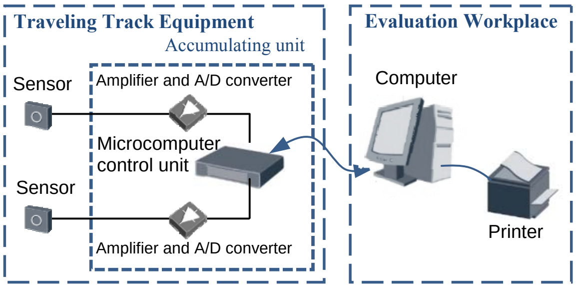

Fig. 1. Data accumulation and processing

Because it was necessary to apply the device on mobile equipment, if possible it had to be shock-resistant, small and be able to function autonomously for long periods under all weather conditions and without power supply. The last condition involved a simple and quick data transfer in the visualization computer. The visualization computer was intended to process the recorded data from the accumulating unit offline. Its application software had to cooperate with the operating system. Next, we will focus on the structure of the measurement and evaluation chain contained in the programmed microcomputer rather than on the structure of the measuring device.

3. MEASUREMENT CHAIN AND ITS ORGANISATION

The measurement chain whose structure is illustrated in Fig.2 has been created to measure, to perform primary filtration, and to record. Theory and practical realization of the experimental measuring process is described in [14]. The whole chain is highly automated and requires minimal human interference. It consists of sensors, measurement amplifiers, analog-digital converters, and an accumulating and recording unit which is computer-controlled. The specific parameters of the used analog-digital converter are subject of the working team know-how. The design for the recording equipment had to allow for the requirements concerning possible occurrence of errors which could influence the measurement results, namely:

- amplitude accuracy that can be significantly disturbed if an amplifier works in a non-linear area or exceeds the frequency band. It can manifest especially dangerously in the pulse phenomena which occur at abrupt collisions, etc. In long-term recordings, such as our case, accuracy may be disrupted also by the effects of an inadequate stability of some parts;
- phase accuracy, if we are interested in mutual statistical characteristics and transfer functions of the measurement system. Phase distortion may occur in the telemetric system of the amplifiers and the subsequent processing, filtrating, and recording in the accumulating unit memory;
- frequency accuracy;
- noise distortion of the signal during the recording. The noise can be generated, among others, by various electrical devices and instruments.

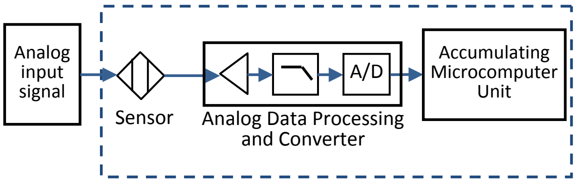

Fig. 2. Measurement chain structure

In our case the monitored process is characterized by the time course of the mechanical quantity we measure electrically, i.e. by using sensors that transform the change in the physical parameter into the change in the electrical signal. The choice of the sensor type depends directly on the measured quantity. In our case, passive strain gauge sensors are used. A strain gauge sensor's ability to discern corresponds to the relative strain of about 1μStrain ($\varepsilon = 10^{-6}$). In our view, the bridge configuration of the strain gauge sensor belongs to one of the most accurate and most often used evaluation methods. The recommended supply frequency is 2–5 kHz. To subdue linearity error, to reduce temperature dependence of the evaluation circuits and to increase sensitivity, it is more beneficial to use a strain gauge bridge supplied by constant current. Non-linearity in such a configuration is approximately half of the strain gauge bridge supplied by constant voltage. Measurements conducted in a high noise environment require a higher supply voltage. Higher voltage consequently increases not only the system's resilience to noise but also the demands on its power supply performance and the drift due to the raised temperature of the strain gauges. This fact impacts the battery's capacity and subsequently its dimensions very significantly when the mobile telemetric system is battery-powered.

The strain gauge measuring sensors are arranged in the half of the strain gauge bridge connection in such a way that there is ensured automatic temperature compensation.

4. SIGNAL SAMPLING

Processing the measured data in a computer requires them to be transformed by an analog-to-digital converter into numeral value sequences. The procedure of process sampling lies in recording the amplitude values at equidistant time intervals Δt. With the maximum frequency of the analysed process known in advance, the appropriate Δt interval is chosen according to the Shannon-Kotelnik criterion

$$f_{vz} = 1/\Delta t > 2.f_{max} \quad (1)$$

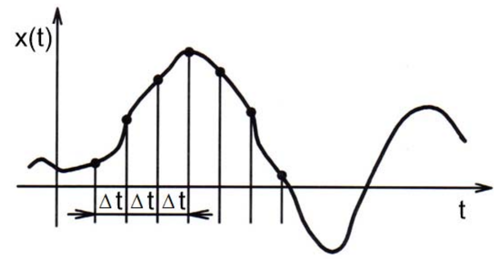

Fig. 3. Signal sampling

In practical applications, the sampling frequency range $f_{vz} = (2.5 \text{ to } 3.0)f_{max}$ is usually chosen in the calculation of the basic process characteristics. In our case we were required to acquire the random process characteristics defined by the set of local maxima and minima of the elementary process. For this reason, we chose a higher sample frequency $f_{vz} = (8 \text{ to } 10)f_{max}$

5. SYSTEM STRUCTURE

The operational load history, which is usually defined by a rain-flow matrix, provides the critical input for evaluating the durability of traveling track elements in railcars. Long-time observation is important for determining residual life because it enables the structure to be monitored during the entire operating time. It provides us with accurate information about the effects of the individual loads. The resulting rain-flow matrix is two-parametric; so besides an amplitude it also includes a medium voltage value, or alternatively a relative strain value. The electrical signal that is sensor-generated is processed in several successive blocks. The simplified sequence is illustrated in Fig. 4.

Other circuits dedicated to signal conditioning modify the signal levels; extract only those frequencies (filtration) that are relevant to further processing; and adjust and adapt the circuit impedance. The samples are directed to the input of the converter which transforms the amplitude value into a binary number. The signal from a sensor that has been conditioned and digitized can be uploaded for instance via a standard serial interface to a personal computer, and can be processed and visualized by applying well-known procedures used in discrete mathematics, statistics, etc. [5]

The block structure of the accumulating unit is illustrated in Fig. 5.

It comprises three main modules; namely a measuring module, a service module and a battery. The measuring module's core consists of a microcomputer control unit that runs the whole module. The service module is a stand-alone microcomputer-controlled unit. It connects to the measuring module via a simple serial interface. It can but need not be included in the measuring device. It is used to visualize and to set some measuring module's parameters such as amplifier

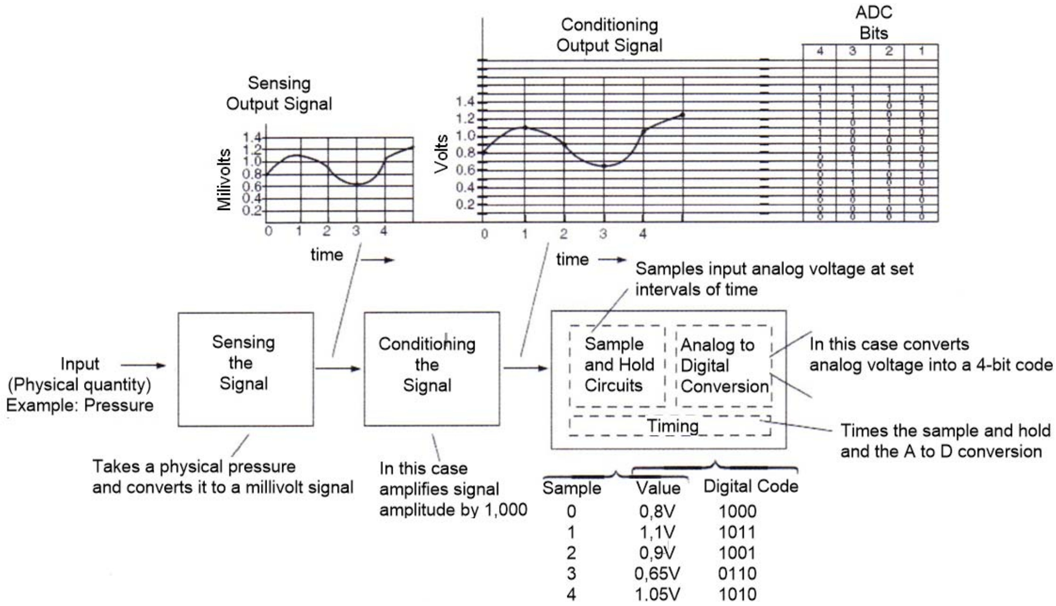

Fig.4. Basic device functions during signal processing

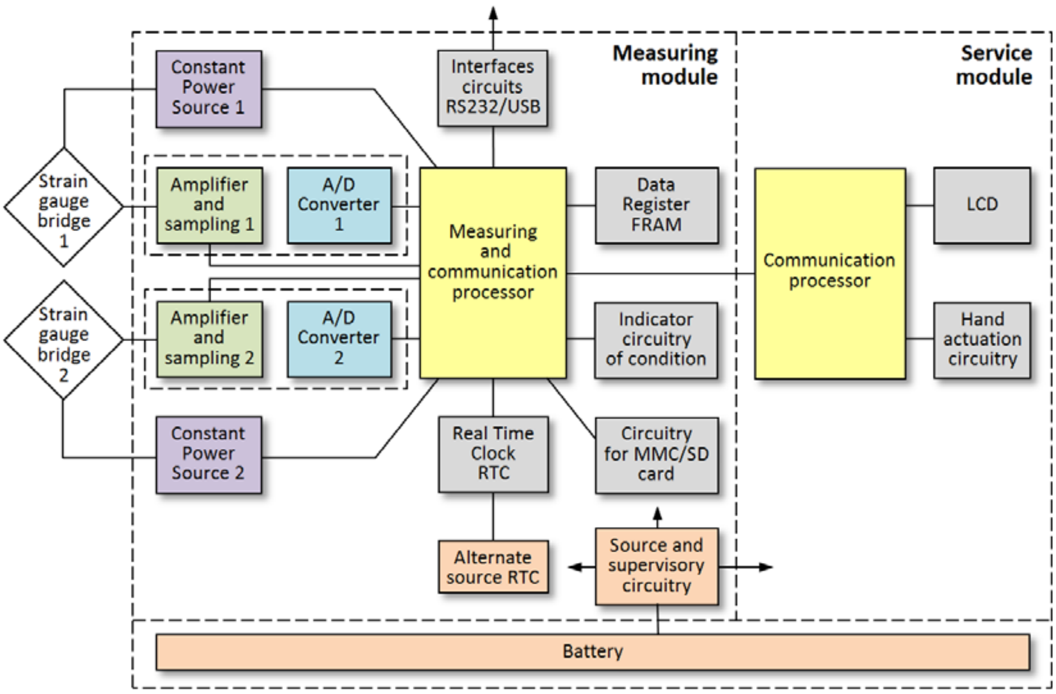

Fig. 5. Accumulating unit

gains or current date and time in the RTC circuit, etc. An easy to replace battery with a large capacity is the main component of the power supply unit. Its voltage serves to produce the necessary power supply levels for the measuring and the service modules. To create the necessary power supply levels, combinations of linear and impulse stabilizers are used with respect to the adequate stability of the power supply voltage and the possible occurrence of interference.

6. SOFTWARE

The software in the microcomputer control unit renders the sampling process; it controls the whole measurement, creates the rain-flow matrices, and stores the data in the memory. The signal elaboration for creation of the rain-flow ranges is presented in [6, 7, 8]. It also includes some basic functions which provide communication with the service module and the external interface for the connection to a personal computer.

The software in the service module provides convenient user communication and features a simple keyboard and an LCD display; alternatively, it can be used to set the measuring module's parameters.

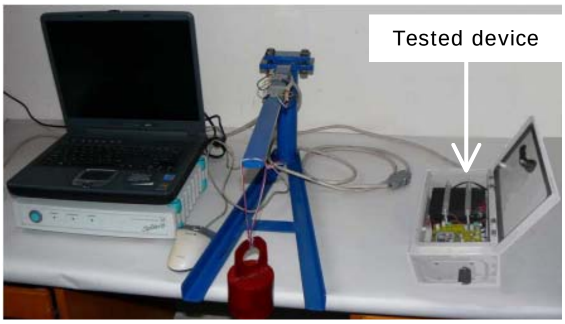

Fig. 6. Beam of constant strength connected to the computer and the tested device

The signal from one of the sensors was recorded by the tested device, while the signal from the other sensor was uploaded to an external computer using a HMB Spider 8 measuring strain gauge apparatus.
The normal stress measurement was taken in the measuring points while a load of a known weight (Fig. 6) was applied to the beam.

Only the values measured during a 10-second time interval in which the normal stress values stabilized at a constant level were considered representative. The measurement was repeated 8 times (Tab. 1). The applied value of sampling frequency was 100 Hz in this case.
The stress values calculated in the points where the sensors were glued were 24.04 MPa. The greatest percentage difference between the measured and the calculated normal stress values in the measured point 1 was 5.1 % .

The measured normal stress values were also used to determine the statistical position characteristics (modus, median, mean value) and the variability characteristics (selective standard deviation, scattering, and coefficient of variation) which are listed in Tab. 2.

Tab. 1 Measured normal stress values

Measurement number	Measuring point	
	1	2
1	25.11	25.14
2	25.14	25.18
3	25.18	25.14
4	25.22	25.18
5	25.18	25.18
6	25.18	25.22
7	25.22	25.18
8	25.26	25.22

Tab. 2 Statistical characteristics of measured normal stress values

	Measuring point 1	Measuring point 2
Modus	25.18	25.18
Median	25.18	25.18
Mean value	25.1865	25.184
Selective standard deviation	0.0364	0.0295
Selective scattering	0.0013	0.0009
Coefficient of variation	0.145	0.117

Based on the coefficient of variation the theoretical distribution type can be assumed. The coefficients of variation according to Tab. 2 are less than 0.3 and according to [12] it is possible to assume agreement with normal distribution. The Jarque-Bera test conducted concurrently in Matlab confirmed the agreement with normal distribution. The Jarque-Bera test measures the difference between skewness and kurtosis in normal distribution. If the number of samples is small, it is more appropriate to use the Lilliefors test (a special case of the Kolmogorov-Smirnov goodness-of-fit test). When the normality of the measured values was confirmed by the strain gauge apparatus and the black box, it was possible to use the parametric tests of the mean value difference (T-test) and the scattering difference (F-test) to ascertain the differences between the sample files. In parallel, a non-parametric Kolmogorov-Smirnov test was also conducted. The choice of the tested criterion used to assess the significance of the differences between two mean values varies on whether the corresponding scatterings are statistically significantly different or not.

To confirm the assumption that the scatterings calculated from the measured data were not statistically different, a parametric test of significance between two different variances (F-test) was conducted. The test criterion $F=S_1^2/S_2^2$, where S_1^2 and S_2^2 denote process scattering with the number of samples N_1 and N_2; while the numerator must be the larger of the scatterings, so that $F \geq 1$

[13]. The null hypothesis in the test was verified by the inequality $F<F_{5,2}$ of the tested F criterion with the critical value $F_{5,2}$ [10, 11]. The critical value was determined by the number of degrees of freedom $k_1=N_1-1$ and $k_2=N_2-1$ from the table of critical values listed in [13] in Appendix VI.

The results of the performed tests (F-test, T-test, Kolmogorov-Smirnov test) have confirmed that the data measured by the Spider8 strain gauge apparatus and the data measured by the black box are not statistically significantly different and are in good agreement.

6. SUMMARY

The device was applied and tested on a selected railcar. It evaluates the time course of the strain online in the point where the sensor was mounted. The time course of the strain is processed and recorded in a data file which contains a rain-flow matrix. After the data is transferred to the visualization computer, the processing software can estimate the residual life in the monitored structural elements of a railcar at any given moment of the operation. This device enables potential failures to be predicted with sufficient lead time. The proposed design ensures increasing of reliability and safety during operation; for railcars in this specific case.

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