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Long-term monitoring of strains in a real operation of structures

Vladimír Chmelko[1], Martin Garan[2]

[1] Faculty of Mechanical Engineering, Regional Technological Institute, University of West Bohemia in Pilsen, Univerzitní 22, 306 14 Plzeň, vladimir.chmelko@stuba.sk
[2] Slovak University of Technology in Bratislava, Faculty of Mechanical Engineering, Institute of applied mechanics and mechatronics, Námestie slobody 17, 812 31 Bratislava, Slovak republic, martin.garan@stuba.sk

Abstract – In most of cases the structural condition monitoring [1] allows to receive significant states or values in a real operation of that structure, such as:

- change in value of safety coefficient by reason of arising overload or non-standard operation mode during service
- vibrations increasing by reason of change in toughness of the structure
- increasing of fatigue damage accumulation in a critical point or section by reason of change in variable stress amplitudes

In this paper, there is presented the extended concept of compensation for elimination of unwanted offset change that can appear during long-term monitoring of the strain signal. The method of this compensation is shown and realized for performing the monitoring process on a real structure of pipeline system where as sensors were used the strain gauges.

I. INTRODUCTION

The real structures are generally multi-axially loaded in a real operation. Before any monitoring process is realized on any technical structure, first it is very important to identify the most loaded point in a critical section in order to determine significant loading process for that structure. The problem is more complex because the position of that point can change during operational loading. On the other-hand the direction of maximum strain (stress) can also change depending on type of loading situations. Also if we want to acquire the proper process of the strain (stress) by sensing in that most loaded point it is necessary to deploy the strain gauges along the critical section very carefully and thoughtfully. Let us note that the evaluation process of principal strains (stresses) in the most loaded point must be evaluated at instant time throughout the monitoring process and also all other monitoring tasks must be completed in a real time. Let us note that for acquiring the accurate signal considering the long-term monitoring process it is very important to take care of choosing the right sensor (e.g. strain gauge) and apply it in the correct position in critical structure place.

II. THE PROPER SENSOR CHOICE

At the present time, there are more options for using the sensors in the area of loadings sensing for a long-time period such as strain gauges, fiber optic sensing of strains (FBG), digital image correlation method (DIC) (for strains measuring), vibrating string gauges (VSG), etc. In consideration of problems that can arise while using particular method for instance the (DIC) where there is a problem with a huge amount of measured data and also requirement of high level light intensity to obtain the relevant results. As an another example let us mention the well-known problem with stability of measured signal during the long-time monitoring process where the signal allocates unwanted change in magnitude offset. This is a usual problem for sensors like FBG (they do not hold the right offset for a long-time period). The usage of VSG sensors also brings a lot of problems with frequency range or higher measurement costs. If the interest is focused on long-term sensing of loadings for any structures the strain gauges from the huge group of sensors seem to be still the most practical and the best solution to acquire relevant records of signals.

Note that, relevant data acquisition by using strain gauges it is very important to take care about proper signal compensation for temperature effect. The traditional temperature compensation (that is recommended by producers of gauges [2]) rests in using the balancing strain gauge, gauge with balancing winding or thermocouple. This way of compensation can solve the problem with the thermal dependency of the wire resistance and also the thermal expansion of material for monitoring structure. Note that, for long-term monitoring processes of strains this method of compensation is in physical layer insufficient for proper measuring [3]. Problem of unwanted additional offset change of signal magnitude can be to solve and eliminate by using the circuit layout that is displayed in Fig. 1. This method involves the signal compensation for entire measuring chain. As is displayed in Fig. 1, the final signal compensation is executed on a level of measuring application that is used differential data handling from measuring channel and channel with balancing strain gauge (for every measuring channels except thermal channel).

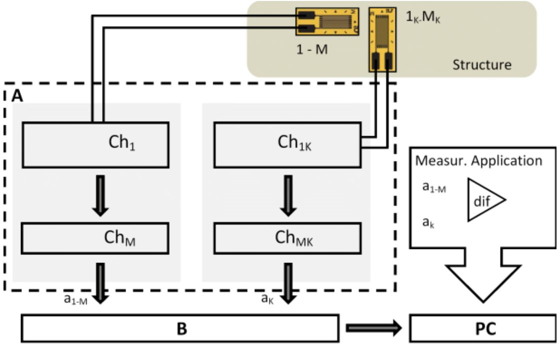

Fig.1 1÷M – strain gauges; $1_K \div M_K$ – thermal ballancing strain gauge; $Ch_1 \div Ch_M$ – measuring channel; A– multi-channels measuring module; B – multi-modules measuring base; PC – computer with measuring application

III. METHOD OF STRAIN SIGNALS PROCESSING FOR ANNULAR CROSS-SECTION OF PIPELINE SYSTEM

The Analysis using FE method can help to acquire information about the structure in cases where the critical sections on that structure are not so clearly identifiable. Another problem is how to deploy the sensors along the critical section in a right direction and position. In such case it is very important to take care for right deployment of sensors in the right position and direction to determine the position of that most loaded point in critical section. For every types of cross-sections, it is possible to find such proper deployment of sensors not only for circular shapes (pipes). One of the most general case is an annular cross-section of the pressured pipeline which is the most common used type of the shape. The marginal loading except the internal pressure can cause additional external bending moment, torque and other additional normal forces (e.g. as a result of thermal dilatations). Considering the cross-section of annular shape, there is necessary to use minimum of 6 strain gauges for clear determination of critical loading point of the cross-section assuming that proportional and non-proportional loading for well-known direction of the transversal force [4]. For annular cross-sections is necessary to perform circumferentially deployment of the strain gauges in order to separate the individual components of loading (Fig. 2). From the analysis of stress-strain state by Mohr's circle which was published in work [5] the results show that by using the strain rosette of gauges with angle 90^o is possible to separate the elongation (measured by axial strain gauges) from the shear strain (measured by revolved strain gauges integrated in rosette).

Deployment of the strain gages circumferentially along the annular cross-section in the spacing of 120^o is necessary for separation of bending from normal forces. The rosette placed at the point of transversal force action (in the case of well-known direction of the gravitational force) measures only the shear strain from the torque. In case when the direction of transversal force is unknown it is necessary to use three rosettes in spacing of 120^o along the annular cross-section and then separate the shear strain from the torque. The individual components of strain (that are displayed in Fig. 2.) allow to determine the most loaded point of the cross-section.

Further analysis of the stress-strain state on the surface for circular or annular cross-sections reveal the possibility of separation of the individual strain components which allows to calculate the strain induced by normal force as

$$\varepsilon_N = \frac{1}{3}\left(\varepsilon_i + \varepsilon_{ii} + \varepsilon_{iii}\right), \tag{1}$$

as well as calculate the maximum strain induced by the bending moment using the following Eq. 2.

$$\varepsilon_B = \frac{2}{3}\sqrt{\varepsilon_i^2 + \varepsilon_{ii}^2 + \varepsilon_{iii}^2 - \left(\varepsilon_i . \varepsilon_{ii} + \varepsilon_{ii} . \varepsilon_{iii} + \varepsilon_i . \varepsilon_{iii}\right)} \tag{2}$$

The unique deployment of strain sensors also enables to derive the following equation for determination of the angle for bending moment vector (see Fig. 2)

$$tg\alpha = \frac{\sqrt{3}\left(\varepsilon_{ii} - \varepsilon_{iii}\right)}{2.\varepsilon_i - \varepsilon_{ii} - \varepsilon_{iii}} \tag{3}$$

Difference between the strain values measured by skewed strain gauges in 90^o rosette equals to the shear strain and can by calculated as

$$\gamma_T = \varepsilon_{iiia} - \varepsilon_{iiib} \tag{4}$$

In the case where the strain rosette is placed in the point of transversal force direction the shear strain is induced only by the torque. The most loaded point in the critical section is given by maximum strain from the bending moment because all other strains obtain constant value on the outer surface. Its position can be monitored by applying the (Eq. 3). On the basis of the (Eq. (1) and Eq. (2)) and relations according the Mohr´s circle it is possible to determine the components of planar strain in the most loaded point at the surface for critical section by following expressions

$$\varepsilon_x = \varepsilon_N + \varepsilon_B = \left(\frac{\varepsilon_i + \varepsilon_{ii} + \varepsilon_{iii}}{3}\right) + \frac{2}{3}\sqrt{\varepsilon_i^2 + \varepsilon_{ii}^2 + \varepsilon_{iii}^2 - \varepsilon_i\varepsilon_{ii} - \varepsilon_{ii}\varepsilon_{iii} - \varepsilon_i\varepsilon_{iii}}$$

$$\varepsilon_y = \varepsilon_{iiia} + \varepsilon_{iiib} - \varepsilon_x$$

$$\frac{\gamma}{2} = \frac{\varepsilon_{iiib} - \varepsilon_{iiia}}{2} \tag{5}$$

where ε_i, ε_{ii}, ε_{iii} are the values of strain in axial direction requiring the thermal compensation

ε_N, ε_B are the values of strain from the normal force resp. from the bending moment

ε_x, ε_y, γ are the components of planar strain state.

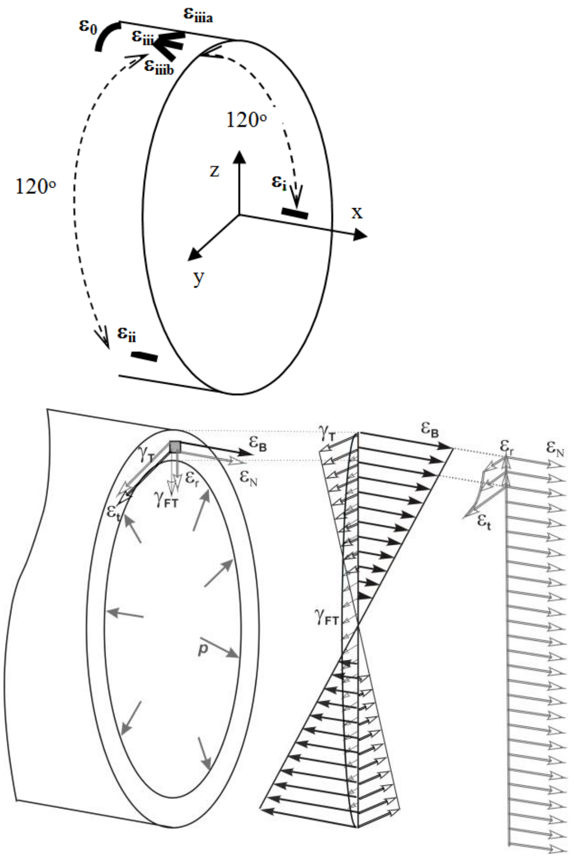

Fig. 2. Deployment of the strain gages circumferentially along the annular cross-section in the spacing of 120^o (rosette in this point for transversal force in the vertical direction) allowing separation of the individual components of loading (ε_N – strain from normal force, ε_B – strain from bending moment, γ_T – shear strain from torque moment, γ_{FT} – shear strain from transversal force, ε_r – strain from internal pressure in the radial direction, ε_t – strain from internal pressure in the tangential direction).

Then the values of the principal strains are

$$\varepsilon_1 = \frac{\varepsilon_x + \varepsilon_y}{2} + \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma}{2}\right)^2}$$

$$\varepsilon_2 = \frac{\varepsilon_x + \varepsilon_y}{2} - \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \left(\frac{\gamma}{2}\right)^2} \qquad (6)$$

In radial direction the component of the strain induced by internal pressure is given by following expression

$$\varepsilon_3 = -\frac{\varepsilon_0 .2.h}{D_S} \qquad (7)$$

where ε_0 is a strain in tangential direction of pipeline cross-section (see Fig. 2)

h is the thickness of pipeline wall
Ds is mean diameter of the pipeline

Using the Tresca's hypothesis registered in the ASME (stress intensity) for this type of structure [6] the overall strain is possible to calculate as

$$\varepsilon_{red} = max(\varepsilon_1, \varepsilon_2) - \varepsilon_3 \qquad (8)$$

Direction of the overall strain in the most loaded point at every instant time given by (Eq. 8) is possible to calculate and record by well-known expression for direction of the principal strain as follows

$$tg2\varphi_0 = \frac{\gamma}{\varepsilon_x - \varepsilon_y} \qquad (9)$$

The angle φ_0 outlines the direction between the 1st principal strain and the x-axis. The plane of the maximum shear strain is inclined about 45° from this 1st principal strain. Note that, all magnitudes involving the strains (Eqs. 6-8), or the angles for position of critical point (Eq. 3) and critical plane direction (Eq. 9) are time depending magnitudes and they must be calculated in a real time during the monitoring process [7, 8].

IV. EXAMPLES OF REALIZATIONS ON REAL STRUCTURES AND OBTAINED RESULTS

In-time monitoring system that monitors the fatigue damage, dangerous vibrations and static safety of the structure was installed on the gas pipeline system at the transit courtyard of the gas company in year 2011 (Fig. 3). This monitoring system continuously evaluates increments of the fatigue damage in 9 critical cross-sections. The cyclic properties of material were acquired by direct cyclic tests on the specimens of materials from which was the pipeline created [9]. Stress diagram of overall loading process in one critical place of the pipeline is displayed in (Fig. 4).

Stresses were calculated using the (Eq. 8) and then multiplied by Young's modulus for better visualization in diagram. Significant amplitudes of that loading were induced by slopes and shutdowns of the pressure in compressor as it is possible to see in (Fig. 4). That means the operation of the pipeline was safe in a view of the fatigue crack occurrence. In the monitoring period at the other section in different locality of the transit courtyard, the monitoring system recorded high descent of the mean value for overall loading (see Fig. 5). From measured data was possible to identify the reason of that descent (position of the most loaded point by Eq. 3) – the main reason was additional bending stress that appeared as result of the subsoil decrease because of the effect of previous more raining period. The measured loading processes in Fig. 4 and Fig.5 are results of long-time monitoring period in a real operation under outdoor conditions. Stability of the off-set (mean values of the signal) is obvious (see Fig. 4). Note that, for both cases of monitoring systems (Fig. 4 and Fig.5) was used the same approach of temperature compensation and the other additional measuring device compensation which was described in this paper. So, from resulting diagrams is possible to conclude that this approach of compensation brings really satisfactory results for acquiring signals without any flowing mean value of the signal which was proved by long-term monitoring testing on real structures.

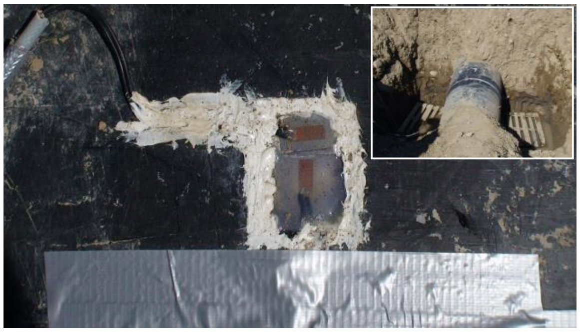

Fig.3 Example of installed strain gauges a) along the circumference of the pipeline, b) with detail including the compensation sensor

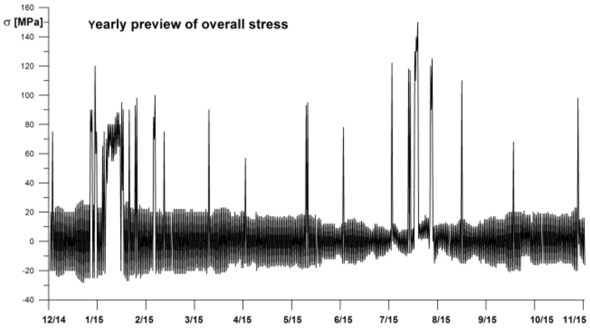

Fig. 4 The loading process development of the overall maximum stress in critical point of the pipeline (Eq.8) multiplied by Young´s modulus.

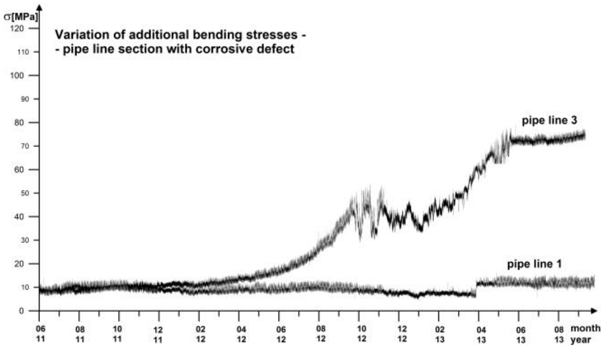

Fig. 5. Increasing of the mean stress in the reason of additional bending loading that occurred by unexpected decrease of subsoil of pipeline system (pipe 3) in the monitored section of the transit courtyard.

V. CONCLUSIONS

The contribution was devoted to the problem of long-term monitoring of measured strains using the strain gauges. The measured processes are used as an input for in-time monitoring system which monitors the fatigue damage, dangerous vibrations as well as static safety of the structure (this monitoring system was installed on the gas pipeline system at the transit courtyard). For performing the measuring tasks there is used unique deployment of the strain gauges along the critical pipe section. This deployment allows to identify the most loaded point in that critical monitoring section. In addition, using this unique deployment is possible to pursue the change of maximum stress vector for evaluation the multiaxial fatigue damage. Stability of the measuring chain offset throughout the long-term monitoring process of strains on the structure is ensured by unique way of compensation. During monitoring is compensated not only the thermal expansion of the sensors and also incoming wires but also there is compensated each channel of particular measuring device. The stability of mean values for measured signals as a result of successful compensation method are presented by long-time measuring records in the form of loading processes.

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