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ESA as a Significant Tool for Intensification of Structural Elements of Pipe Systems

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Abstract Complex mechanical systems intended for gas transport are formed by complicated technological piping units. Their main components are gas pipelines, compressor stations, connection and distribution nodes, etc. As a part of their operation, monitoring but especially within long-term intensification of their technical competence, it is necessary to solve a variety of complex technical problems. These are mainly related to monitoring and prediction of lifespan of critical system elements, then also to monitoring corrosion damaged pipeline and related repairs and eventually to rectification of older bridges and other temporary or unsatisfactory technical solutions. Important interacting negative factors in the process are gradual degradation of used material, presence of residual stresses, etc. Solving these problems is unthinkable without active application of experimental modeling, relevant experimental methods and corresponding hardware and software. This mainly includes means of modal analysis and analysis of deformation and mechanical stresses. The article also presents relevant conclusions from solving environment of specific technical problems in the conditions of gas piping transport system in the Slovak Republic.

Keywords: *experimental stress analysis, piping systems, limit state, dynamic loading, fatigue*

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1. Introduction

Remote transport of gaseous and liquid media such as natural gas and oil is very effectively realized using piping systems - gas and oil pipelines. The piping system for natural gas transport in the Slovak Republic in east - west direction is represented by transport system of Eustream company. It is a set of four parallel pipe lines with a diameter of 1200 and 1400 mm with a total length of more than 2500 km, continually built since 1967. The system has a pronounced transit character and for strategic reasons is technically and technologically adapted to bidirectional gas flow.

Parts of the piping systems are complex technological units, mainly compressor and pumping stations, border transfer stations, connection and distribution nodes, underground storage facilities etc.

2. Danger of Limit State Formation in Elements of Piping System

The mentioned technological units are exposed to a range of negative influences. As a consequence of their effect piping system can ultimately reach an undesirable limit state. This means it abruptly loses its functional and utility characteristics or gradual change of functional and utility characteristics reaches critical level and the system or structure fails. Reaching a certain type or form of limit state of any of the elements of gas transport system now depends on the dynamics of damage accumulation. This is a function of structural and substructural state of the used material, technology and construction characteristics of piping elements and conditions of their use. It is also a function of time and intensity of impact, size and nature of changes of external and internal factors. And each of them separately or in superposition can trigger a limit state. The external or operational factors affecting elements of a piping system may include mechanical loading, temperature, environment, or presence of energy fields. The internal factors may then include technological and metallurgical characteristics as a method for producing construction elements and nodes, state of structure and substructure of piping system materials, etc. The most serious negative factors have proved to be variable force loading and degradation effect of aggressive environment. These often act in conjunction with present residual stresses, particularly near the weld joints and in combination with unsatisfactory structural state or improper baseline characteristics of the used material. The result then can be a limit state and failure of piping system elements, mostly by microplastic or macroplastic deformation, fracture from mechanical loading or fatigue, local damage localized on the surface or in a certain volume of piping or technological element, etc.

3. Problems Related to Intensification of Piping Systems

All technical devices for gas transport are of strategic character and their failure often leads to fatal consequences, economic damage, loss of life etc. Therefore it is vital to constantly monitor and intensify each element of a transport system. This is related to solving a wide range of problems, mainly:

- monitoring and prediction of lifespan of pipe yard elements;
- monitoring of pipeline damaged by corrosion and its repairs;
- rectification of older bridges and other temporary or unsatisfactory technical solutions.

Current method of solving the mentioned technical problems is application of experimental modeling as main tool for data acquisition and analysis from real, i.e. operational loading. This mainly entails methods and technical means on basis of experimental stress analysis (ESA) and experimental modal analysis. All experimental methods and procedures, measuring chains, technical and program resources applied in processes of experimental modeling are described further, e.g. in [1,2].

3.1. Monitoring and Prediction of Lifespan of Compressor Stations Pipe Yards

Flow of gas in gas pipelines is realized by its pressurization in compressor station. However when affected by passive resistances gas pressure in pipeline continually decreases with increasing distance. This is why gas pressure needs to be constantly renewed in other compressor stations, which replenish the needed pressure in pipelines and keep it at levels defined by standards. Pipe yards of compressor stations consist of complex technological network system of mutually intersecting overground and underground pipelines, turns (Figure 1), valves and turbo-compressors with total installed power of as much as few hundreds MW. The systems are at the same time exposed to various dynamic stress effects and events, resulting mainly from pressure pulsation in the pipeline. That forms of non-stationary gas flow through individual elements of pipeline and individual turbo-compressors. In these conditions individual elements of pipe yards as well as entire systems are extremely susceptible to fatigue failure and forming of limit state of fatigue [3,4,5].

Figure 1. View of part of technological unit of compressor station

The degradation of used material and change of its baseline mechanical properties may also contribute to an increased risk of fatigue failure. Where appropriate, these changes were investigated by testing the respective samples. This was done by static tensile tests of the weld joint in the direction perpendicular to the pipe axis and of basic material in a direction perpendicular and parallel to the pipe axis. Furthermore, conducted were experimental dynamic bending impact tests with sharp notch Charpy type V and fatigue properties tests of tensile and bending nature of the basic material and weld joint [6,7,8,9].

Critical negative factor in relation to fatigue failure may also be the presence of tensile residual stresses, especially in proximity of weld joints. Where needed, the analysis of residual stresses was realized by the method of drilling directly from the original sample of pipeline in proximity of weld joint (Figure 2) [10]. Used experimental measuring chain is shown in Figure 3 or Figure 4.

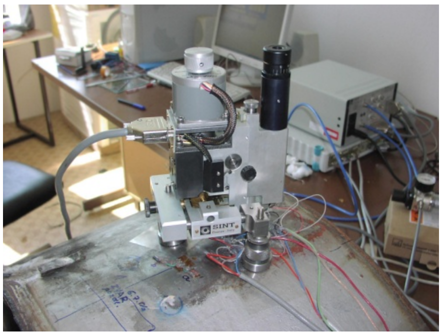

Figure 2. Determination of residual stresses in proximity of weld joint on a sample of pipeline of compressor station

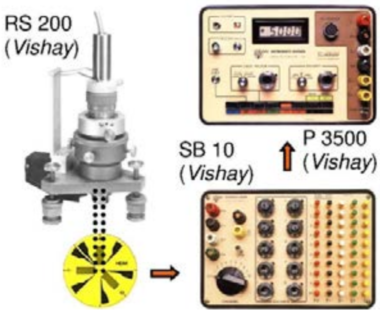

Figure 3. Experimental measuring chain for determining residual stresses by the drilling method using system RS 200

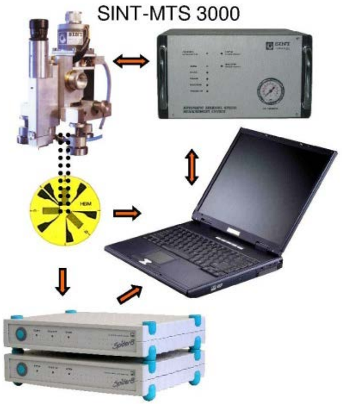

Figure 4. Experimental measuring chain for determining residual stresses by the drilling method using system SINT-MTS 3000

Acceptable and relatively simple way of decreasing negative dynamic effects and respective amplitudes of mechanical stresses and concentrations of stresses in proximity of supports is substituting solid supports with flexible vibro-isolation elements with fullmetal shock absorbers (Figure 5) [11]. This solution also allows height adjustment of pipe axis as well as control of reaction force in support. The solution is also advantageous for the optional change of stiffness with preloading with respect to possible frequency tuning of a system with dampening effect and also for large carrying capacity and small size.

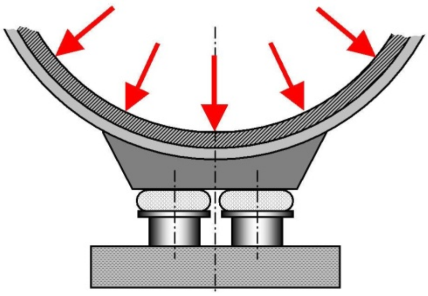

Figure 5. Integration method of vibroisolation mat in pipe support of the compressor station

Based on initial experimental analyses of pipe yards we detected compound oscillation containing a wide range of frequency components with various frequencies. In such case individual compounds can be determined only through modal frequency analysis from dependency of their amplitudes on oscillation frequency. Through frequency analysis it is possible to get information about individual oscillation components, sources of mechanical oscillation, as well as characteristics of mechanical systems impacted by mechanical oscillation. This way we can discern even the resonant properties of systems during change of various frequency components with time and decide the values of parameters important for operation.

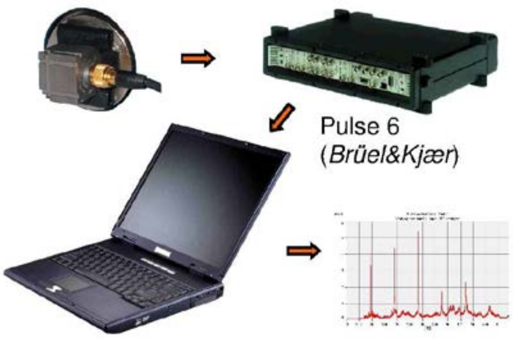

Figure 6. Experimental measuring chain for determining the parameters of dynamic processes using system PULSE 6

Figure 7. Detail view of applied vibro-isolation mat and triaxial acceleration sensor

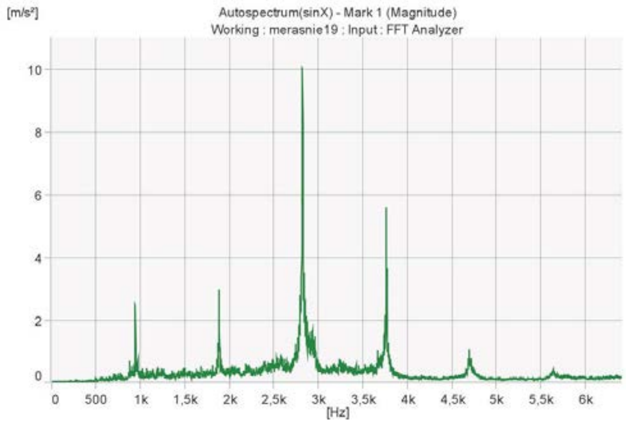

Figure 8. Frequency dependence of accelerations measured on pipe turn of compressor station

Experimental measuring chain for the purpose of modal analysis had the form shown on Figure 6. Figure 7 is the view of applied vibro-isolation mat and triaxial acceleration sensor on the support of piping system of compressor station. Figure 8 shows one of many acquired dependencies. It represents frequency dependence of accelerations measured on pipe turn of the compressor station.

At the same time a number of dynamic tensiometric measurements were performed with the aim of acquiring information for analysis of deformation and stresses [12]. The used experimental measuring chain had the form shown in Figure 9.

Figure 9. Experimental measuring chain for determining relative deformations using dynamic tensiometric system SPIDER 8

Based on the amount of experimentally acquired results the state of individual elements of pipe yard and the state of degradation of the used material could be concluded. Other conclusions were related to prediction of remaining lifespan expressed for example in years either with or without using vibro-isolation elements. Among the solved problems was reliability assessment of compressor station operation in relation to its rebuilding and reconstruction for the possibility of operation at compression ratios increased by 2,8 %.

3.2. Pressurized Sleeve as a Method of Repairing Corrosion Damaged Pipeline

Part of the intensification of piping systems is their protection against damage, or critical sized damage.

Overground and underground piping is in fact affected by a variety of negative factors. One is chemically aggressive environment, which can result in corrosive damage of the pipeline. In the event of such damage, it is necessary to proceed with repairs. Typical repair process involves removal and replacement of the damaged part. More convenient and more sophisticated repair process is application of pressurized sleeve. This is an effective method of repair which suffices with just a slight reduction of pressure in the pipeline. It is therefore unnecessary to cut the pipe or otherwise render it inoperative. Pressurized sleeve is formed by deploying two covers, screwed or welded together, where the newly formed space between the pipeline and the sleeve is filled with curable substance [13,14,15].

The fundamental problem of applying pressurized sleeves technology is development of new, or selection of existing, substance. This plastic substance (typically two-component) has to meet a number of many times even conflicting requirements [16]. These pertain mainly to processing and functional characteristics. It has to be possible to prepare greater amount of the substance (150 l) in 5 minutes, it can not be gassed, has to have sufficiently low viscosity for at least 30 minutes with curing within 48 hours. At the same time it cannot be heated nor can it change volume, must be inert to steel, have sufficient cohesion as well as strong adhesion to steel, must be non-absorbing and moisture resistant, stable over time etc.

Selected materials were first subjected to tests for evaluation of properties, necessary for processing of materials (viscosity, temperature differences and volume changes after air curing) and tests of mechanical properties (modulus of elasticity, strength and elongation). In the second step the materials were subjected to tests of curing under pressure. Their goal was to determine if curing occurs at higher pressures (up to 10 MPa) and identify changes in material during curing under pressure.

Figure 10. The complete set of pressurizing and measuring system for determining processing and functional characteristics of the filling substance

An important goal was determining the rate of pressure drop in a closed pressurized container by gradual volume decrease of the filling substance. We elected an experimental method of determining behavior monitoring of the substance during its polymerization in enclosed volume by means of its pressurization in a special test container. Pressure size, temperature and relative elongation in tangential and meridian direction of the pressurized container according to Figure 10 was continuously recorded using tensiometric measuring chain according to Figure 11. The resulting history of loading for one of many tested substances resembles Figure 12. Based on stress history we obtained time dependencies of the rate of pressure drop of curing substance shown in Figure 13. After each such experiment the test container has been cut open to check the state of filling.

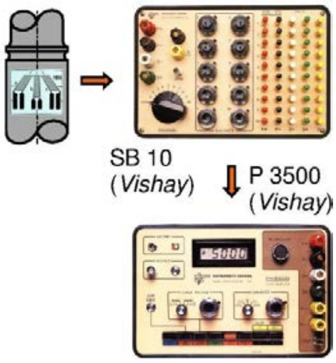

Figure 11. Experimental measuring chain for determining relative deformations using static tensiometric system Vishay

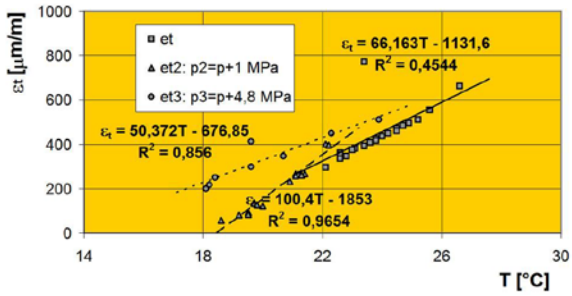

Figure 12. Temperature dependence of strain of the test container on its surface in tangential direction

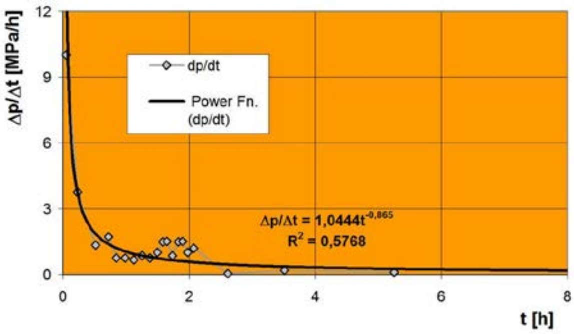

Figure 13. Time dependence of rate of pressure drop of the examined substance in test pressure container

Based on these and other findings the specific selected substance was approved or rejected. We also acquired valuable knowledge related to correction and optimization of technology and application of pressurized sleeves.

3.3. Rectification of Gas Transport Bridges

Part of the construction of individual branches of the pipeline was overcoming natural terrain obstacles such as mountain ranges and river flows. Technical and technological solutions used during construction were, however, sometimes makeshift and corresponded to material and technological possibilities of that day and age. In the case of overcoming watercourses three different methods of bridging were applied using piping bridges, differing structurally and technologically: three-joint dam arch, three-section dam straight continuous joint girder and fixed self-supporting pipeline. Today it can be seen that these solutions are long surpassed and safety, economic and operational reasons demanded rectification of gas piping bridges using modern solutions. This is represented by laying the pipeline underneath the water obstacles using so called benders. This solution was applied to several watercourses in the Slovak Republic.

In the process of rectification during renovation of old overground and realization of new underground solutions a problem arose in the partial coexistence of both solutions. New solutions were in fact implemented in the vicinity of the original bridges. Part of the necessary intensive landscaping were quakes and vibrations, resulting for example due to hammering of sheet pilings during creation of so called sheet-pile walls. It was rightly assumed that these modifications implemented in the vicinity of piping bridges at the end of their lifespan can adversely affect the existing structure and could damage it.

It was decided to acquire information about behavior of critical parts of the pipeline on old pipeline bridges during the simulation of construction modifications (Figure 14) and use it as a basis for the analysis of given situation. The methods and means of ESA became the main source of relevant data collection. The used measure and evaluation chains mostly had the configuration according to Figure 9 and Figure 11. From the large series of data obtained by the static and dynamic tensiometric measurement with the goal of determining the construction response it is possible to state the dependence in Figure 15. This is the frequency dependence of amplitude spectrum of relative elongations recalculated to uniaxial state of stress. Measurement was performed on the piping crossing DN 1400 of the fourth line of transit pipeline over one the river flows. Tensiometric sensors were located on the surface of self-supporting double arch gas pipeline near its inlet into the ground.

Figure 14. Existing and newly realized gas pipelines over a river flow

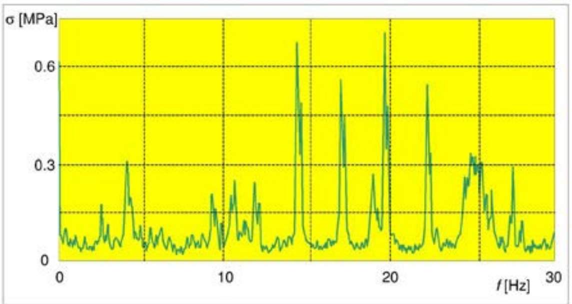

Figure 15. Frequency dependence of amplitude spectrum of relative elongations recalculated to uniaxial state of stress

Based on these and other findings were drawn the conclusions about the rate of negative impact of construction work on existing constructs. Specific recommendations were stated and relevant measures were taken to prevent negative effects.

4. Conclusion

Methods and means of experimental stress analysis (ESA) and experimental modal analysis are invaluable sources of information about behavior and response of such a complex mechanical system as the gas piping system. Based solely on these experimentally acquired data it is possible to take into account the often unknown external factors critically affecting the construction. Conclusions listed at the end of chapters 3.1. to 3.3. in major way contributed to intensification of potential further operation and monitoring of individual construction elements and whole set-up of the gas transport system.

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