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ANALYSIS OF THE INFLUENCE OF FRICTION FORCE ON THE STRAINS OF GAS PIPELINE USING THE HILBERT-HUANG TRANSFORM

ANALIZA WPŁYWU SIŁ TARCIA NA STAN ODKSZTAŁCEŃ RURY PRZESYŁOWEJ GAZOCIĄGU PRZY ZASTOSOWANIU TRANSFORMACJI HILBERTA-HUANGA

Key words:

Hilbert-Huang transform, gas pipeline, pipe, friction, strain, vibration

Słowa kluczowe:

transformacja Hilberta-Huanga, gazociąg, rura, tarcie, odkształcenie, drganie

Abstract

The aim of the study was to determine the effect of friction forces on strains of a gas pipeline pipe in conditions of static and dynamic load. The experiments were conducted on a 28-metre section of pipe laid in quartz sand haunching.

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The source of dynamic loads was artificially generated soil vibration of a pulse character, which can be interpreted as seismic-like waves of mining origin. The static loads were applied by means of an actuator, which allowed the setting of different values of tension force acting along the pipe axis. The dynamic strain and vibration acceleration of the pipeline were measured during the experiments at different values of tension forces. The recorded signals were subjected to the time-domain decomposition by using the Hilbert-Huang transform. The method allows for the correct decomposition of the primary signal that describes the non-stationary and nonlinear phenomena as a sum of quasi-harmonic components whose amplitudes and frequencies are the parametric functions of time. The analysis included the determination of the influence of friction force in contact between the pipe and the sand haunching on the parameters of dynamic strain signals.

INTRODUCTION

Areas with unstable subsoil or seismic activity are a significant hazard for safe operation of pipelines **[L. 1–3]**. They include, amongst others, the areas of mining and transport activities, which can result in subsoil deformation, faults, and tremors of a seismic-like character. In addition to these external forces, the transmission pipes are also subjected to the action of working pressure and the temperature of transported medium. According to the regulations in force, the pipes are laid in soil in the quartz sand haunching. In this case, the main sources of external loads of transmission pipes are static forces and moments caused by friction as a result of contact between the pipe and the haunching. The seismic-like vibration acting on the pipe can change the friction forces in the pipe's contact with the haunching, which change the loads on the structure **[L. 4, 5]**. The control of operating conditions of a pipeline includes monitoring strain and vibration acceleration, and monitoring subsoil vibration acceleration and the subsoil deformation **[L. 6]**. The signals recorded during the monitoring process are analysed using standard Fourier frequency transform (FT) or a short time Fourier transform (STFT). These techniques are effective only in the analysis of linear and stationary (FT), or linear and non-stationary (STFT) phenomena. A new method of signal decomposition in the time domain was developed over the last few years for analysis of phenomena that are nonlinear and non-stationary, which is the HHT (Hilbert-Huang Transform) **[L. 7–9]**.

The paper, based on HHT, presents the impact of friction forces in the contact between the pipe and sand haunching on the values of dynamic signals of the pipe strain. The conditions of applying dynamic impact loads relative to the form of generated seismic-like signals were stabilized during the experiments. The soil parameters and mechanical properties were also constant. Such stabilized conditions were used to examine the impact of seismic-like vibration on the strain in the test section of the pipe for various friction force values. The friction force value, a variable parameter in the experiments, was applied by changing the value of static tension of the transmission pipe section.

HILBERT-HUANG TRANSFORM (HHT) ALGORITHM

The Hilbert-Huang Transform comprises two procedures. The first one developed by Huang **[L. 7]** and known as EMD (*Empirical Mode Decomposition*) involves an adaptive decomposition in the time domain of primary signal $x(t)$ into narrow-band component IMFs (*Intrinsic Mode Function*). The second procedure involves using the Hilbert transform for each component IMF in order to determine the waveform of amplitude, frequency, and phase as a function of time.

The principle of the operation of the EMD algorithm involves an iterative separation from primary signal $x(t)$ of successive component IMFs, each of which must satisfy the following conditions **[L. 7–9]**: The number of extrema and the number of zero crossings must be equal or differ by not more than one, and the average value of the envelope interpolating local maxima and the envelope interpolating local minima is equal to zero.

The process of searching for each ith IMF component $h_i(t)$ involves subtracting the local mean $m_k(t)$ from the signal until the IMF is obtained which satisfies the aforementioned conditions. The local mean has the following form:

$$m_k(t) = \frac{e_{gk}(t) + e_{dk}(t)}{2} \quad \text{for} \quad k = 1, 2, ..., N \tag{1}$$

where k – successive iteration during determination of the i^{th} IMF component, $e_{gk}(t)$ and $e_{dk}(t)$ – upper and lower signal envelope, which are spline function of the 3^{rd} degree interpolating local signal maxima and minima, respectively.

While decomposing the signal $x(t)$, we obtain the following in successive steps of the EMD algorithm individual IMF components: $h_1(t)$, $h_2(t)$, ..., $h_N(t)$ and residual signal $r_N(t)$ so that the following equation is finally satisfied **[L. 8, 9]**:

$$x(t) = \sum_{i=1}^{N} h_i(t) + r_N(t) \tag{2}$$

Each IMF component $h_i(t)$ is described by slowly varying functions of amplitude $A_i(t)$ and pulsation $\omega_i(t)$.

$$h_i(t) = A_i(t)\cos\left(\int_0^t \omega_i(t)dt\right) \quad \text{for} \quad i \in [1 \div N] \tag{3}$$

If $\hat{h}(t)$ is the Hilbert transform of signal $h(t)$, then using the following properties of analytical signal:

$$H(t) = h(t) + j\hat{h}(t)\,, \tag{4}$$

we can calculate the instantaneous amplitude $A_i(t)$, pulsation $\omega_i(t)$ and frequency $f_i(t)$ of each ith IMF component using the following relationships:

$$A_i(t) = \pm\sqrt{h_i^2(t) + \hat{h}_i^2(t)} \tag{5}$$

and

$$\omega_i(t) = 2\cdot\pi\cdot f_i(t) = \frac{d\psi_i(t)}{dt} = \frac{d}{dt}\left(\arctan\frac{\hat{h}_i(t)}{h_i(t)}\right). \tag{6}$$

TEST STAND AND DESCRIPTION OF THE EXPERIMENT

The location of the experiment near the village of Gogołowa in Upper Silesia was chosen based on an analysis of forecast deformation of mining areas and also the level of failures of the gas network used in the area. The section of the gas transmission pipe chosen for the experiment was located in the area classified as mining category II in which hard coal was mined. During the few years before the experiment, there had been seismic-like quakes in the area caused by the mining activing, and the energy of the seismic-like quakes reached $5.7\cdot10^7$ J. The gas pipeline was built of D = 50 mm diameter steel pipe, with a wall thickness of g = 3.8 mm, and it was laid in sand haunching 0.8 m below grade without compensators protecting it against the deformation of the terrain. A 28-metre long straight section of transmission pipe was selected for the experiment. The pipe was a part of a distribution gas network in which about 30 failures had been recorded during the three years preceding the experiments.

Figure 1 presents a schematic drawing of the stand for experimental testing of the dynamic loading of gas pipeline. The strain gauges glued onto the pipe in each measuring point P_1 and P_3 were connected in sets of strain gauge bridges, which allowed the recording of the longitudinal strain of the pipe ε_x, ε_y, ε_z in each point separately **[L. 6]**.

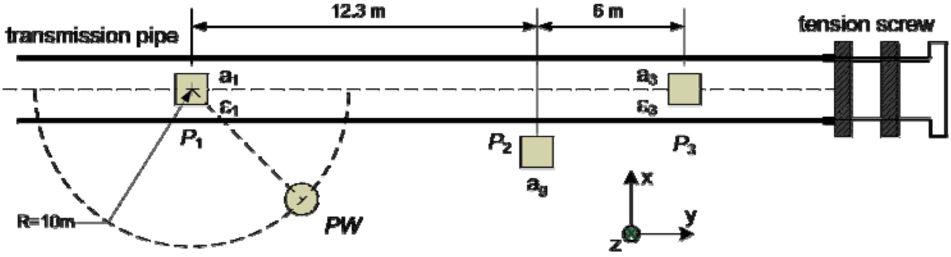

Fig. 1. Schematic drawing of the stand for static and dynamic loading of the transmission pipe
Rys. 1. Schemat stanowiska do statycznych i dynamicznych obciążeń rury przesyłowej

Figure 1 also shows the orientation of the system of coordinates relative to the pipeline. Axis y follows the pipeline axis, and axes x and z are perpendicular to the pipeline axis, with axis x being horizontal and axis z vertical relative to the ground. Subscripts x and z indicate that the values of measured longitudinal strain ε_x and ε_z are caused by bending moments acting on the pipeline along axis x or z, respectively. Subscript y indicates that measured longitudinal strain ε_y is caused by the action of the axial force along the pipeline. The adequate number of strain gauges and way they were connected in bridges ensured the necessary compensation of the impact of temperature and components that were not measured. The measuring system used allowed a simultaneous measurement and recording of pipeline vibrations a_x, a_y, and a_z. Very close to the pipe, at measuring point P_2 **(Fig. 1)**, a three-axial accelerometer was placed to measure the acceleration of ground vibration a_{gx},, a_{gy}, and a_{gz}. During the experiment, the impact loads were applied at point *PW* and the location of this point changed along the 10-metre radius circle with measuring point P_1 as the centre. The tested section of transmission pipe was subjected to static tensile tests, thus changing the values of friction forces in contact with sand haunching. Impact loads were applied at the same time, which generated vibrations in the subsoil and in the pipe. The average friction force at the 18.3 m section between points P_1 and P_3 **(Fig. 1)** is equal to

$$F_T = F_3 - F_1 \tag{7}$$

where
F_T – average friction force at the section between points P_1 and P_3,
F_1 and F_3 – longitudinal forces acting along the pipe axis at points P_1 and P_3.

Taking into account the measurement results of longitudinal strain ε_y at points P_1 and P_3 we obtain the following:

$$F_T = S \cdot \left(\sigma_{y3} - \sigma_{y1}\right) = S \cdot E \cdot \left(\varepsilon_{y3} - \varepsilon_{y1}\right) \tag{8}$$

where
σ_{y1}, σ_{y3} – stresses caused by the force acting along the pipeline axis, at points P_1 and P_3,
ε_{y1}, ε_{y3} – measured strains caused by the force acting along the pipeline axis, at points P_1 and P_3,
S – area of pipe cross-section,
E –Young's modulus of the pipe material.

The strain gauge transducers were prepared in laboratory conditions where they also were calibrated using a standard force sensor. The prepared transducers were installed on the tested pipeline section (at points P_1 and P_3 according to **Fig. 1**). After calibration, the conversion function of the transducers to measure the friction force F_T (8) is as follows:

$$F_T = F_3 - F_1 = 152.6 \cdot \left(\varepsilon_{y3} - \varepsilon_{y1}\right) \tag{9}$$

where, for strains ε_y expressed in ‰, force F_T is expressed in kN.

The experiments were conducted for three different values of static longitudinal force F_3, measured at point P_3, equal to 20.3 kN, 94.8 kN, and 121.5 kN. The force was applied with a specially designed screw actuator. These tension force values correspond to the forces occurring in areas classified as mining categories I to IV.

The pipe tensioned by means of the longitudinal force was subjected to dynamic pulses that were caused by dropping a 1200 kg weight from about 2.7 m at place marked as *PW*. As a result of vibration, the dynamic signals of pipe strain were obtained and recorded. The responses of the acceleration of soil and pipe vibration were recorded simultaneously. The signals were recorded with a sampling frequency of f_p = 1200 Hz, and the duration of a single recording was T = 3.33 s and the number of samples was 4000.

EXPERIMENT RESULTS

Figures 2 and **3** present examples of longitudinal strain waveform at points P_1 and P_3 recorded during the dynamic experiments **(Fig. 1)** while the pipe was simultaneously loaded with a static tension force of F_3 = 94.8 kN.

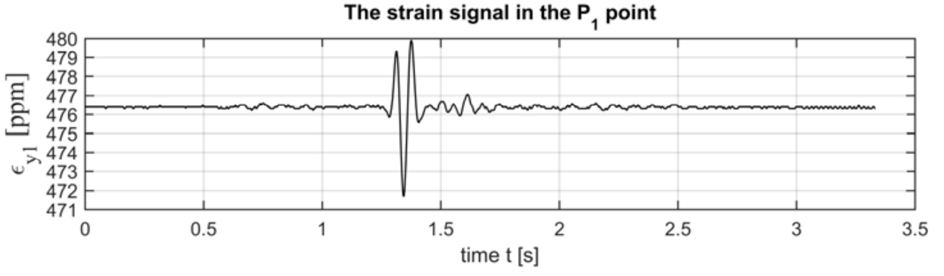

Fig. 2. Signal of pipe strain ε_{y1} at point P_1
Rys. 2. Sygnał odkształceń ε_{y1} rury w punkcie P_1

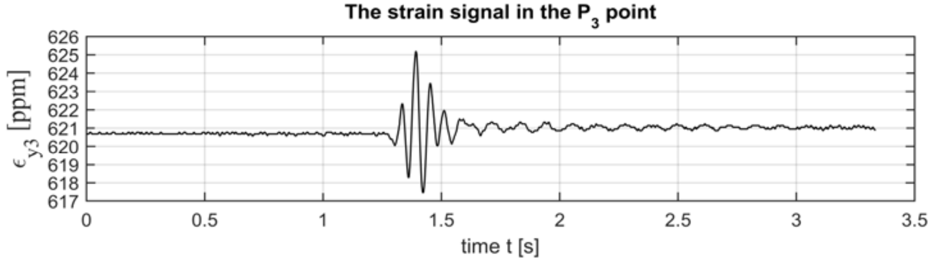

Fig. 3. Signal of pipe strain ε_{y3} at point P_3
Rys. 3. Sygnał odkształceń ε_{y3} rury w punkcie P_3

These signals and the strain signals were also recorded for other values of tension force 20.3 kN and 121.5 kN, and they were decomposed using the Hilbert-Huang transform. IMF components were determined for each signal (according to (2)) along with the instantaneous values of amplitude and frequency of these components according to (5) and (6). **Figure 4** presents time waveforms of the IMF components of strain signal ε_{y3} shown in **Fig. 3** for static tension force of F_3 = 94.8 kN. **Figures 5** and **6** present instantaneous waveforms of frequencies and amplitudes of that signal's IMF components.

Mean values of strain signals $\bar{\varepsilon}_{y1}$ and $\bar{\varepsilon}_{y3}$ are a measure of static forces F_1 and F_3 acting along the pipeline axis at points P_1 and P_3. Using the value of calibration coefficient (9), the $\bar{\varepsilon}_{y1}$ and $\bar{\varepsilon}_{y3}$ values expressed in ppm can be converted to forces expressed in kN as follows:

$$F_1 = 0.1526 \cdot \bar{\varepsilon}_{y1} \quad F_3 = 0.1526 \cdot \bar{\varepsilon}_{y3} \tag{10}$$

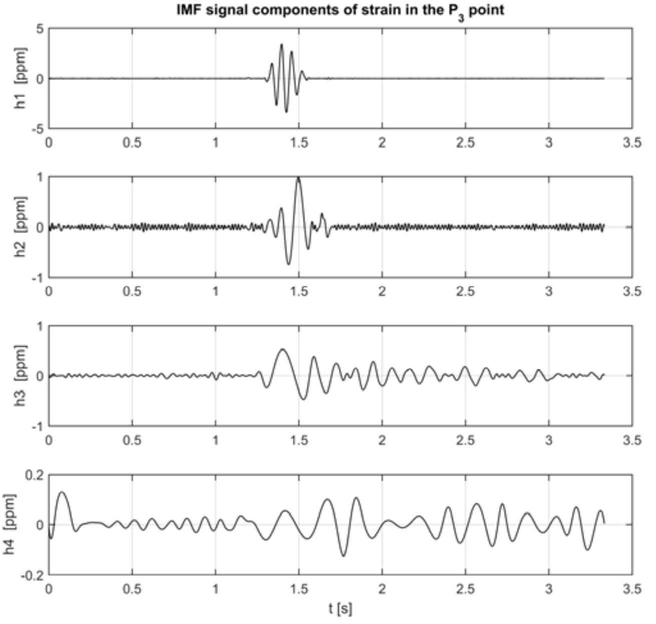

Fig. 4. IMF components of pipe strain signal ε_{y3} (Fig. 3), acc. to (2) and (3)
Rys. 4. Składowe IMF sygnału odkształceń ε_{y3} rury **(Rys. 3)**, zgodnie z (2) i (3)

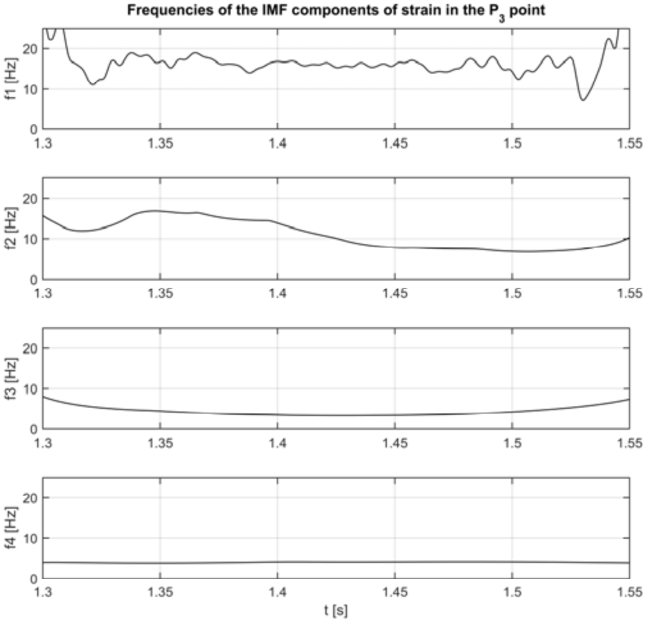

Fig. 5. Instantaneous frequencies of the IMF components of strain signal ε_{y3}, acc. to (6)
Rys. 5. Chwilowe częstotliwości składowych IMF sygnału odkształceń ε_{y3}, zgodnie z (6)

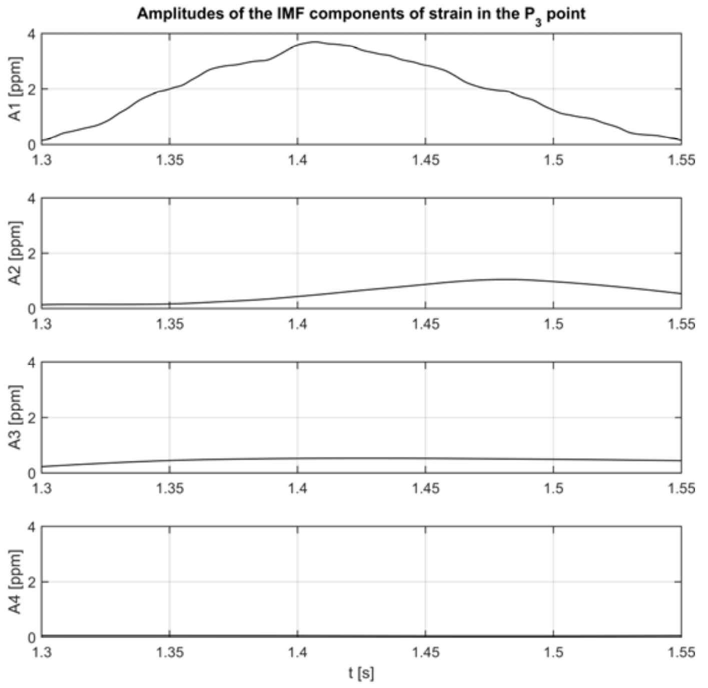

Fig. 6. Instantaneous amplitudes of the IMF components of strain signal ε_{y3}, acc. to (5)
Rys. 6. Chwilowe amplitudy składowych IMF sygnału odkształceń ε_{y3}, zgodnie z (5)

Table 1 presents the calculated values of those forces and of friction force F_T according to (9) for various pipe tension forces. **Table 1** also includes average frequency values f_i (columns 5 and 8 in **Table 1** and **Figure 5**) and maximum amplitude values A_i of the IMF components (columns 6 and 9 in **Table 1** and **Figure 6**) determined for the time interval in which the pulse reaction of dynamic strain signals takes place (For the example shown in **Figures 3** to 6, it is the interval 1.3–1.55 s).

The presented results indicate that, when the pipe tension force F_3 increases, the average friction force F_T in contact between the pipe and quartz haunching on the tested 18.3-metre section between P_1 and P_3 first increases and later decreases. This information allows one to control the condition of contact between the pipe and quartz haunching. The condition of the contact is also indicated by the difference between mean strain values $\bar{\varepsilon}_{y1}$ and $\bar{\varepsilon}_{y3}$ at points P_1 and P_3. On the basis of data in **Table 1**, it was concluded that increase in pipe tension force F_1 and F_3 causes a rise of the average frequency f_1 of the dominating IMF component (dominating due to the value of amplitude A_1) both at P_3 (14.6 Hz, 16.9 Hz, 17.9 Hz) and P_1 (16.1 Hz, 17.0 Hz, 25.0 Hz).

Table 1. Decomposition results of the pipe strain signals
Tabela 1. Wyniki dekompozycji sygnału odkształcenia wzdłużnego rury

Tension forces and friction force			Strain at P_3 ε_{y3}			Strain at P_1 ε_{y1}		
F_3 [kN]	F_1 [kN]	$F_T = F_3 - F_1$ [kN]	$\bar{\varepsilon}_{y3}$ [ppm]	f_i [Hz]	A_i [ppm]	$\bar{\varepsilon}_{y1}$ [ppm]	f_i [Hz]	A_i [ppm]
20.3	11.1	9.2	133.0	14.6 13.1 8.5 –	1.70 0.61 0.55 –	72.7	16.1 12.1 8.9 5.3	4.41 2.00 1.31 0.32
94.8	72.7	22.1	621.2	16.9 10.9 4.4 4.1	3.69 1.05 0.53 0.06	476.4	17.0 12.8 9.1 7.6	2.36 1.89 0.42 0.039
121.5	105.6	15.9	796.2	17.9 11.8 5.3 3.3	4.75 1.98 0.72 0.49	692.0	25.0 15.3 8.5 4.2	1.37 0.39 0.38 0.13

CONCLUSIONS

The conducted experiments and the analysis of the strain signals of the transmission pipe using the Hilbert-Huang transform justify the following statements:

- The applied HHT analysis enables a decomposition of signals describing the nonlinear and non-stationary character of strains of a transmission pipe in a gas pipeline to the IMF components and the determination of instantaneous values of component frequencies and amplitudes.
- The average value of frequency f_i of the strain signal in a chosen point on the pipeline determined based on the dominating IMF component is monotonically ascending along with the increase of the longitudinal force acting on the pipe.
- The difference between mean strain signal values on the tested pipeline section allows one to calculate the average friction force according to (9).
- The average friction force F_T in contact between the pipe and quartz haunching (**Table 1** column 3) on the tested 18.3-metre section between P_1 and P_3 first increases to 22.1 kN and later decreases. The value of friction force thus allows one to control the state of contact force on the tested pipeline section.

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Streszczenie

Celem badań było określenie wpływu sił tarcia na stan odkształceń rury przesyłowej gazociągu w warunkach obciążenia statycznego oraz dynamicznego. Eksperymenty przeprowadzono na 28-metrowym odcinku rury ułożonej standardowo w gruncie w obsypce z piasku kwarcowego. Źródłem obciążeń dynamicznych rury przesyłowej w trakcie eksperymentów były wywoływane sztucznie drgania gruntu o charakterze impulsowym, które można interpretować jako fale parasejsmiczne pochodzenia górniczego. Obciążenia statyczne rury wywoływane były za pomocą siłownika, umożliwiającego zadawanie różnych wartości siły naciągu działającej wzdłuż jej osi. Podczas eksperymentów dla różnych wartości sił naciągu rury zmierzono sygnały dynamiczne jej odkształceń oraz przyspieszeń drgań. Zarejestrowane sygnały poddano dekompozycji w dziedzinie czasu z zastosowaniem transformacji Hilberta-Huanga. Metoda umożliwia poprawną dekompozycję sygnału pierwotnego na sumę quasi-harmonicznych składowych, których amplitudy oraz częstotliwości są parametrycznymi funkcjami czasu. W ramach analizy określono wpływ wartości siły tarcia w kontakcie rury z obsypką piaskową na wartości parametrów dynamicznych sygnałów odkształceń.