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The Analysis Regarding the Opportunity of Considering the Effect of Periodic Aerodynamic Loads Generated by Wind on the Durability of Aerial Transportation Pipes

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Abstract

The wind action on the aerial segments of the trunk pipe line (in case of crossing over obstacles) can have important effect regarding the pipe durability. The presented paper is putting forward an opportunity analysis of taking in consideration the action of periodical aerodynamic loads generated by vortices layers which can be detach behind of a pipe placed in a air flow generated by wind. Therefore, there are defined the speed wind domains for which stable vortices are generated and are determined the correspondent pipe diameter. The most important conclusion of the presented study is that the influence of the periodical aerodynamic loads on the pipe durability is significant only in special conditions: high wind speeds, big distance between the supports poles (accidental). For this special situations, it is effectuated the numerical determination of a pipe durability, quantified in number of cycles, for which the pipe wall is penetrated by a crack.
Key words: periodic aerodynamic loads, wind speed, durability

Introduction

Due to the wind action on the different mechanical structures or singular bodies which can oscillate, and so on the aerial transportation pipes, are generated dynamic, aero elastic and periodical phenomena. The periodic aerodynamic loads, generated by the wind activity, have frequencies that do not depend on the frequency of the considered structure, hence the aerodynamic loads oblige the structure to oscillate in a different mode. The frequency of the periodic aerodynamic force depends of the wind speed and becomes dangerous when is equal with one of the natural frequency of the mechanical structure. Knowing that is impossible to obtain resonance effect, the periodic aerodynamic loads can diminish by fatigue the durability of mechanical structures.

The presented situation takes place when the wind speed has a value big enough to generate important aerodynamic loads (magnitude and frequency) for large periods of time. So, it must be remembered the fact that, for instance, the Crivat (a very powerful winter wind) which affect Moldova, Dobrogea and south-east of Muntenia, it is frequently blows with speeds between 30 and 35 *m/s*, for periods of times that can last some tens of hours. Hence, in January 1966, the speed of this wind, have reached a maximum of 55 *m/s* in Moldova and Baragan.

The trunk pipe lines are generally placed under ground, but in case of crossing over obstacles as rivers or narrow and deep valleys, this pipe lines are positioned at different heights, with respect to the water level, for lengths that can go over hundreds meters. In this areas, the wind can blow frequently with speeds around $20 \div 40\, m/s$.

The diameter of the trunk pipe lines it is between 150 and 1400 mm. Hence, the internal gas transportation network of Romania, measure approximately 11000 km with pipes having the diameter of 150 – 1000 mm. Our country is transited by 570 km of pipes having diameters of 1000 – 1200 mm. The gas pipe Turkey – Austria, which will be made until 2015, is having on the Romanian land a length of 475 km and a diameter of 1400 mm.

Developing conditions of the Karman vortices

On the fluid flow (air) over a round surface, on the cylinder are taking place a limit layer in which is recorded an important speed and pressure variation. Therefore, the limit layer is separated from the cylinder, which leads to formation in downstream of the cylinder of two vortices layers called Karman vortices. Generation of these vortices depends on value of the Reynolds number:

$$R_e = \frac{v \cdot D}{\upsilon} \tag{1}$$

in which: v - wind speed;
υ - kinematical viscosity of the air;
D - external diameter of the pipe.

Thereby, for different values of the Reynolds number, it is possible to define the flowing domains around the cylinder:

- for $40 < R_e < 150$, the vortices layer behind the cylinder is stable.
- for $150 < R_e < 300$ the vortices layer behind the cylinder is not very stable.
- for $300 < R_e < R_{ecr}$, in which the critical value of the Reynolds number is ranging in $1{,}5 \cdot 10^5 \div 3 \cdot 10^5$ domain, the flow is turbulent and the vortices layer, although irregular, is developed behind the cylinder.
- for $R_{ecr} < R_e < 3 \cdot 10^6$, the flow is very turbulent and is not possible to highlight the vortices layer.
- for $R_e > 3{,}5 \cdot 10^6$, appears to restore the alternant vortices layer in turbulent conditions.

For the presented study, are interesting only the flowing conditions for which behind the pipe is developing a stable layer of Karman vortices, simultaneously with values of the Reynolds number typical to air flow around the aerial transportation pipes. Thus, for realistic wind speed, placed between $10 \div 60\, m/s$ and usual dimensions of the external pipe diameter placed between $(0{,}2 \div 1{,}4)\, m$, the values of the Reynolds number is ranging between $1{,}3 \cdot 10^5 \div 6 \cdot 10^6$, typical to the turbulent airflow regime.

It follows that the periodical aerodynamic loads can develop for flowing regime defined by $300 < R_e < R_{ecr}$, only for values of Reynolds number $R_e = (1{,}3 \div 1{,}5) \cdot 10^5$ and in flowing regime defined by $R_e > 3{,}5 \cdot 10^6$, that means for $R_e = 3{,}5 \cdot 10^6 \div 6 \cdot 10^6$, for which behind the cylinder the vortices layer is developed.

The frequency of the periodical aerodynamic load is given by the detachment frequency of the Karman vortices. For calculation of the detachment frequency, is defined the Strouhal number:

$$S = \frac{f \cdot D}{v} \tag{2}$$

In which *D* and *v* have been defined for equation (1) and *f* is the detachment frequency of the vortices.

Considering the detachment pulsation of the vortices:

$$\omega = 2\pi \cdot f \tag{3}$$

we can write:

$$S = \frac{\omega \cdot D}{2\pi \cdot v} \tag{4}$$

On the research literature, the Strouhal number is approximately defined for areas of interest established above:

- $S \approx 0,2$ for $R_e \approx (1,3 \div 1,5) \cdot 10^5$;
- $S \approx 0,27$ for $R_e \approx 3,5 \cdot 10^6 \div 6 \cdot 10^6$.

The periodic aerodynamic load generated by the vortices layer

As is shown in figure 1, the periodic aerodynamic load progress on the cylinder, on the normal direction to the airflow speed and has the direction changing frequency given by the detachment frequency of the vortices.

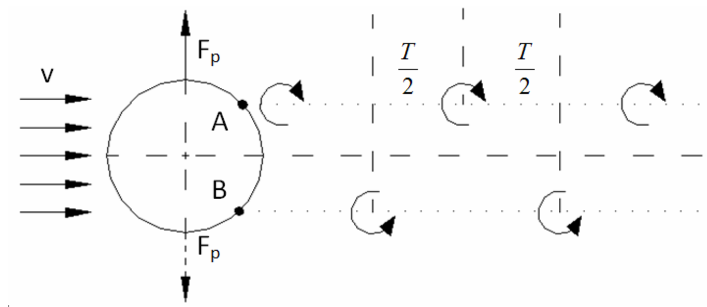

Fig. 1. The Karman vortex sheet

The vortex placed on the cylinder in the detachment point on the upper layer (point A) come off after half period in comparison with the vortex from the inferior layer which come off in point B. The periodic aerodynamic load has the following equation:

$$F_p = \frac{1}{2} \rho \cdot v^2 \cdot c_K \cdot D \cdot \cos \omega t \tag{5}$$

in which: ρ - air density;

v - speed of the air flow;

D - external diameter of the pipe;

ω - detachment vortices pulsation;

c_K - an unitary pulsation coefficient.

For: $R_e \approx (1,3 \div 1,5) \cdot 10^5$; $C_K \approx 0,45$

$R_e \approx (3,5 \div 6) \cdot 10^6$; $C_K \approx 0,5 \div 0,6$

It must be mentioned the fact that equation (5) has been establish considering the hypothesis of plane flow, hence, the F_p load is calculated as acting on the length unit (one meter) from one cylinder having infinite length.

The wind speeds and pipe diameter in the development regime of the vortices layers

Concerning to the conditions $R_e \approx (1{,}3 \div 1{,}5) \cdot 10^5$ and $R_e \approx (3{,}5 \div 6) \cdot 10^6$ which define the regimes for which the vortices layer it is stable behind the cylinder. From the equation $R_e = \frac{v \cdot D}{\upsilon}$ (considering for air $\upsilon = 1{,}48 \cdot 10^{-5}$) it is possible to obtain the equation between the wind speed and the diameter of the pipe:

- $v \cdot D \approx \upsilon \cdot R_e = 1{,}92 \div 2{,}22$ for the first domain;
- $v \cdot D = 5{,}18 \div 8{,}88$ for the second domain.

In the table 1 are presented the possible combination between the wind speed and the pipe diameter.

Table 1. Combination between wind speeds and pipe diameters

Domain	$D[m]$	$v[m/s]$
$R_e = (1{,}35 \div 1{,}5) \cdot 10^5$	0,150	$12{,}8 \div 14{,}8$
	0,20	$9{,}6 \div 11{,}1$
$R_e = (3{,}5 \div 6) \cdot 10^6$	1,100	$47{,}09 \div 80{,}7$
	1,200	$43{,}1 \div 74$
	1,300	$39{,}84 \div 68{,}3$
	1,400	$37 \div 63{,}42$

Numerical determination

An important parameter for studying the effect of the aerodynamic wind loads on the aerial transportation pipes is the distance between the support poles. The distance between two support poles can determine increasing or decreasing of the maximum bending moment from the pipe wall, leading to a maximum stress $\sigma_{\max}$.

Taking in consideration the usual and practical values of the distance between the support poles, is possible to conclude that the periodic aerodynamic loads caused by wind, do not have an important influence on the pipe durability.

However, to draw other conclusions, have been done numerical determination for the distance between support poles equal with 100 meters. Also, the area between supports poles is considered embedded at both ends, and loaded with a intensive distributed force $F_p\,[N/m]$.

The pipe is made from low carbon steel having the following characteristics: strength stress: $\sigma_r = 1034\,N/mm^2$ and yield stress: $\sigma_c = 965\,N/mm^2$.

The durability of the pipe have been determined using the NASGRO 5.01 software and is quantified as numbers of cycles until the crack penetrate the pipe wall. The numerical results are presented in table 2, in which: $D[m]$ – the external pipe diameter, $v[m/s]$ - the wind speed, $F_p\,[N/m]$ - the periodic aerodynamic load, $t[mm]$ - the pipe wall thickness, $\sigma_{\max}\left[N/mm^2\right]$ - the normal maxim stress generated by the pipe bending, $N[cycles]$ - number of cycles needed for crack propagation on the wall thickness, $f[Hz]$ - the frequency of the periodic aerodynamic load.

Table 2. Numerical results

$D[m]$	$v[m/s]$	$F_p[N/m]$	$f[Hz]$	$t[mm]$	$\sigma_{\max}[N/mm^2]$	$N[cycles]$
1,1	46	1454,75	11,29	10	131,17	811973
				12	109,90	1397378
				14	94,71	2254441
	49	1650,68	12,02	10	148,77	588378
				12	124,66	998088
				14	107,43	1572274
1,2	43	1386,75	9,67	10	104,76	1486104
				12	87,79	unlimited
				14	75,62	unlimited
	46	1587,00	10,35	10	119,9	1028396
				12	100,471	1796337
				14	86,55	unlimited
	49	1800,75	11,02	10	136,04	739164
				12	114,0	1265730
				14	98,20	2024772
1,3	40	1300	8,30	10	83,58	unlimited
				12	69,98	unlimited
				14	60,25	unlimited
	43	1502,31	8,9	10	96,59	1882131
				12	80,87	unlimited
				14	69,62	unlimited
	46	1719,25	9,55	10	110,49	1281119
				12	92,50	2303087
				14	79,64	unlimited
	49	1950,81	10,17	10	125,38	914235
				12	104,97	1585645
				14	90,37	2633808
1,4	37	1197,8	7,13	10	66,2	unlimited
				12	55,4	unlimited
				14	47,74	unlimited
	40	1400	7,71	10	77,4	unlimited
				12	64,8	unlimited
				14	55,78	unlimited
	43	1617,8	8,29	10	89,5	unlimited
				12	74,9	unlimited
				14	64,49	unlimited
	46	1851,5	8,87	10	102,39	1585418
				12	85,7	unlimited
				14	73,77	unlimited
	49	2100	9,45	10	116,20	1117945
				12	92,27	2323838
				14	83,73	unlimited

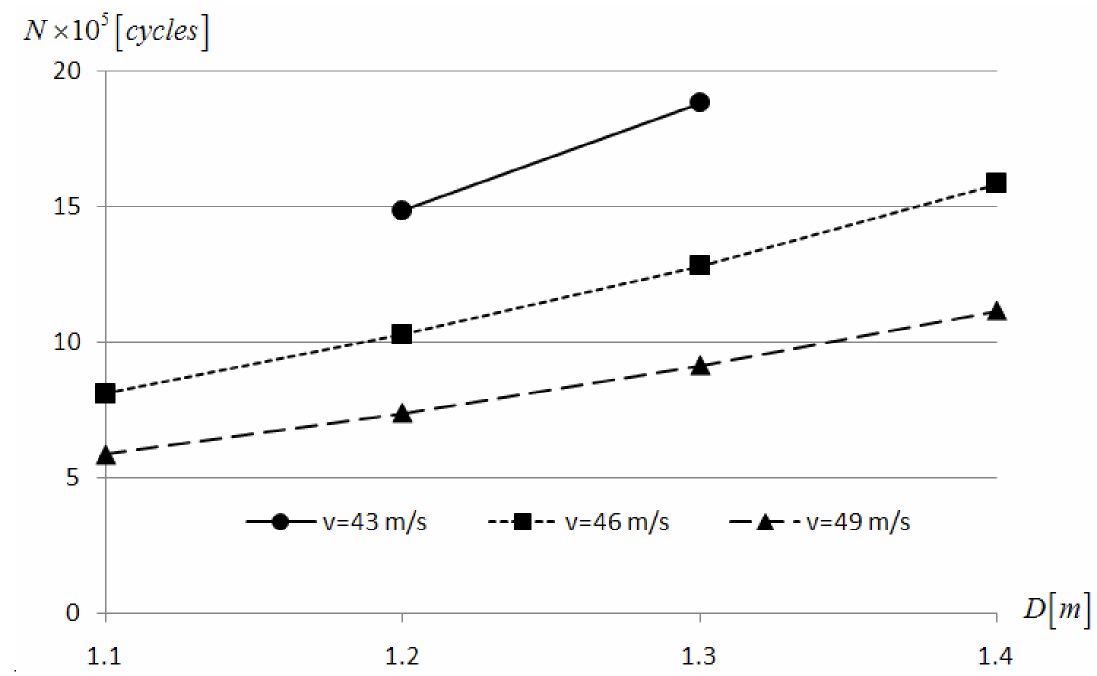

Fig. 2. Correlation *N* - *D*

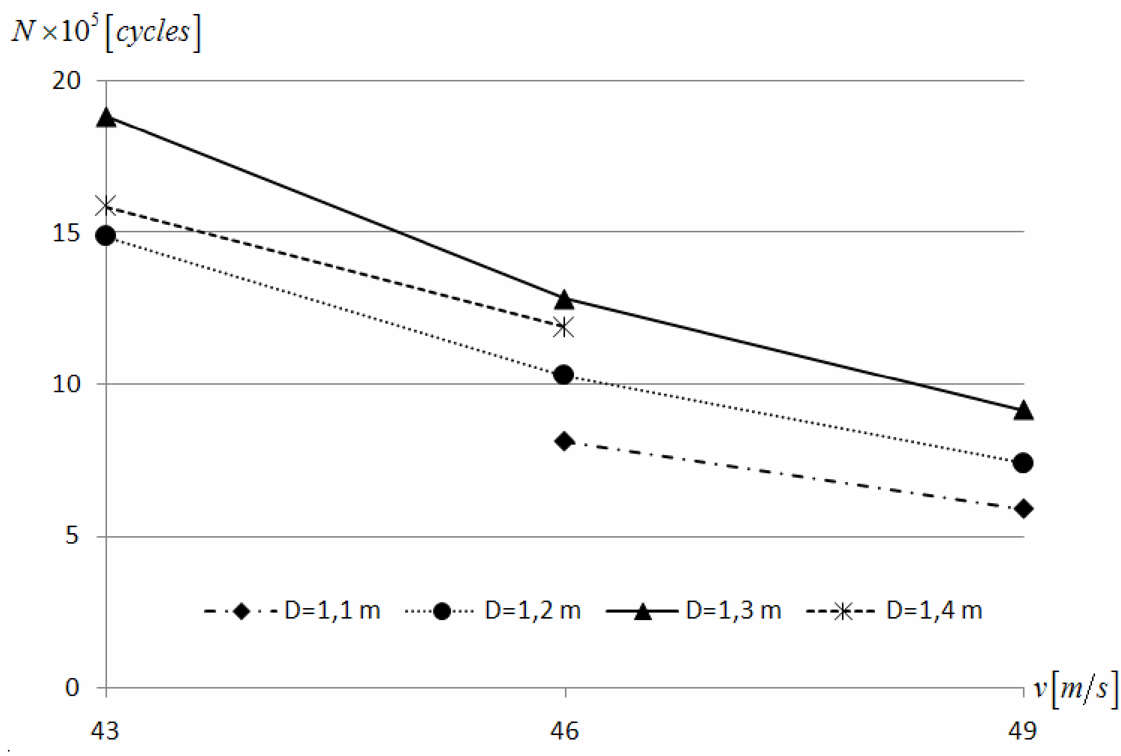

Fig. 3. Correlation $N - v$

In figure 2 and 3 are presented:

- Figure 2 shows the dependency between durability $N[cycles]$ function to the pipe diameter for different speeds of the wind, when the pipe wall thickness is $t = 10mm$;
- Figure 3 shows the dependency between durability $N[cycles]$ function to the wind speed for different diameters of the pipe, when the pipe wall thickness is $t = 10mm$;unlimited

Conclusions

The theoretical study and the simulation that have been cared out conduct us to the following conclusions:

The periodic aerodynamic load is generated only for flowing regimes in which the vortices layer is formed and stabilized. Those regimes are taking place for $R_e = (1,35 \div 1,5)\cdot 10^5$ and $R_e = (3,5 \div 6)\cdot 10^6$.

The domain $R_e = (1,35 \div 1,5)\cdot 10^5$ correspond to some relative small wind speed ($9,6 \div 14,8\, m/s$), the periodic aerodynamic loads having no effect on the durability of the pipes.

The domain $R_e = (3,5 \div 6)\cdot 10^6$ correspond to high wind speed ($37 \div 63\, m/s$) for pipes with diameters $1,1 \div 1,4m$. This values of the wind speed are not very often reached, and is happening during some sever winter storms.

For small distances between the pipe support poles (crossing over obstacles), the stress values are relatively small, and do not affect the life time of the pipe.

It is possible to conclude that destructions of the pipe by forced vibrations generated by the periodic aerodynamic loads caused by wind can occur only in exceptional situations when wind is blowing with high speed and the distance between support poles is high. The obtained numerical results for this situation lead to estimation of the life time of the pipe quantified in number of cycles for which the crack penetrate the pipe wall.

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Analiza privind oportunitatea luării în considerare a forțelor aerodinamice periodice produse de vânt asupra durabilității conductelor de transport

Rezumat

Acțiunea vântului asupra porțiunilor aeriene de conducte magistrale de transport (la trecerea peste obstacole) poate avea efecte importante privind durabilitatea. În articol este expusă o analiză a

oportunităților luării în considerare a acțiunii forțelor aerodinamice periodice dezvoltate de către straturile de vârtejuri case se pot desprinde în spatele unei conducte plasate în curentul de aer produs de vânt. Pentru aceasta, sunt definite domeniile de viteze ale vântului în care se dezvoltă straturi de vârtejuri stabile, se determină valorile corespunzătoare ale diametrelor conductelor. Concluzia cea mai importantă a studiului este că acțiunea forțelor aerodinamice periodice asupra durabilității conductelor nu este însemnată decât în cazuri deosebite: viteze mari ale vântului, distanțe mari între stâlpii de susținere (care se pot produce şi accidental). Pentru astfel de cazuri deosebite, este efectuată şi determinarea numerică a durabilității unei conducte, exprimată în număr de cicli la care se produce străpungerea prin fisurare a peretelui conductei.