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Presentation of an Experimental Approach for the Determination of Mean Velocity in Oscillating Tube Flows Via Hot Wire Anemometry

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Ključne riječi
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Srednja oscilirajuća brzina

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The utilization of constant temperature anemometry (CTA) system for the measurement of mean oscillating velocity of air at negligible compressibility is discussed in this paper. The measurements were conducted at a station of self-excited oscillations in a circular cross sectional pipe following the collapse of the elastic test tube of a Starling resistor in a flow Reynolds number range of 7,000 ≤ Re ≤ 94,000. The cross-sectional traverse of the hot-wire probe at the measurement station in a frequency (*f*) range of 13Hz ≤ *f* ≤ 107Hz were conducted. The cross sectional oscillating velocity profile was determined by using the ensembled averages of oscillating velocity data. The position of the hot-wire probe corresponding to the mean axial oscillating velocity was determined to be approximately 0.755 of pipe radius from the centreline in the covered ranges of Re and *f*.

Prikaz eksperimentalne metode za mjerenje srednje brzine oscilirajućeg toka u cijevi pomoću anemometra s toplom niti

Izvornoznanstveni čalank

U ovom radu je prikazana upotreba anemometra u načinu rada s konstantnom temperaturom za mjerenje srednjih oscilirajućih brzina zraka pri zanemarivoj stlačivosti. Mjerenja su vršena pri samopobudnim oscilacijama u cijevi kružnog poprečnog presjeka postavljene nakon prigušne Starling-ove cijevi, u rasponu Reynoldsove značajke od 7 000 do 94,000. Raspon frekvencija mjerne sonde je u rasponu od 13Hz do 107Hz. Profil oscilirajućih brzina toka zraka u poprečnom presjeku cijevi je određen skupom uprosječenih podataka dobivenih mjerenjem. Pozicija mjerne sonde anemometra s toplom niti u odnosu na srednju aksijalnu brzinu toka zraka je određena da iznosi 0.755 radijusa cijevi od simetrale cijevi za navedene raspone Re značajke i frekvencije.

1. Introduction

In case of fluid flow through collapsible elastic tubes, application of an external pressure which is higher than the internal pressure to the tube walls causes the collapse of the tube with the generation of self-excited oscillations. The flow dynamics with particular emphasis to flow limitation, nature of oscillations has been studied since 1960's due to its relevance to physiological flows [1-4]. Self-excited oscillations following the collapse are unsteady with time-dependent fluctuations in pressure, velocity and flow rate. Therefore in the previous studies time-dependent flow rate was measured with an electromagnetic flow meter in aqueous flows [5]. The velocity measurements were usually conducted by means of Laser Doppler Anemometer [6, 7]. It has been widely observed that self-excited oscillations develop strongly in both of tube wall and flow when the internal minus external pressure across the tube wall is negative. An interaction occurs between flow and the tube-wall; the self-excited oscillations with a multiple frequency mode arise owing to this interaction and as a result the flow field becomes very complicated [8]. In general the oscillations are influenced by both of flowing fluid and tube characteristics. The potential mechanisms inducing the oscillations to emerge were brought out [9].

In the conducted experimental study, elastic test tubes located in the so-called Starling resistor were collapsing with the application of an external pressure, p_e inducing the self-excited oscillations at downstream end of the test tubes. The applicability of a hot-wire anemometer was controlled by using the cross-sectional oscillating velocity profile at a measurement station (x_m) located at discharge pipe of the Starling resistor. The experiments were so devised that the particular influence of oscillation frequency, characteristics of oscillations affected by the collapsible tube parameters were not considered in the covered range of measurements. Since the present study is directed towards an approach with the hot-wire anemometry utilization in the field of self-excited oscillations, physical mechanism of the oscillations is not discussed. The main motivation of the present study is

Symbols / Oznake

A, B, n	- constants in King's Law - konstante King-ovog zakona
c	- constant in the power law - konstanta potencijalne funkcije
D_o	- undeformed test tube diameter - promjer nedeformirane cijevi
f	- frequency of the oscillations - frekvencija oscilacija
h	- thickness of the test tube - debljina stijenke cijevi
L	- length of the test tube - duljina cijevi
N	- number of data - broj podataka
p_e	- external pressure in Starling resistor - vanjski tlak u Starling-ovom otporniku
p_2	- pressure at the exit of the test tube - tlak na izlazu cijevi
r	- radial position from the pipe centre - radijalna udaljenost od središnjice cijevi
R	- pipe radius - polumjer cijevi
R'	- limiting position of the hot-wire probe close to the wall - granični položaj sonde anemometra blizu stjenke cijevi
Re	- flow Reynolds number of steady flow before collapse - Reynoldsov broj stacionarnog toka
t	- time - vrijeme
$\bar{u}$	- mean velocity of steady flow before collapse - prosječna brzina stacionarnog toka
u	- local velocity of steady flow before collapse - lokalna brzina stacionarnog toka
u_i	- local instantaneous velocity - lokalna trenutna brzina
U_e	- effective cooling velocity of the hot wire probe - efektivna brzina hlađenja mjerne sonde
u_{os}	- oscillating flow velocity - brzina oscilirajućeg toka
$u_{os,max}$	- oscillating flow velocity measured at the pipe centre - brzina oscilirajućeg toka mjerena u centru cijevi
$\bar{u}_{os}$	- mean oscillating velocity - osrednjena oscilirajuća brzina
V_A	- output voltage from hot wire anemometer - izlazni napon anemometra s toplom niti
x_m	- measurement station from the exit of the test tube - mjerna točka od izlaznog presjeka cijevi
v	- kinematic viscosity of the fluid - kinematski viskozitet fluida

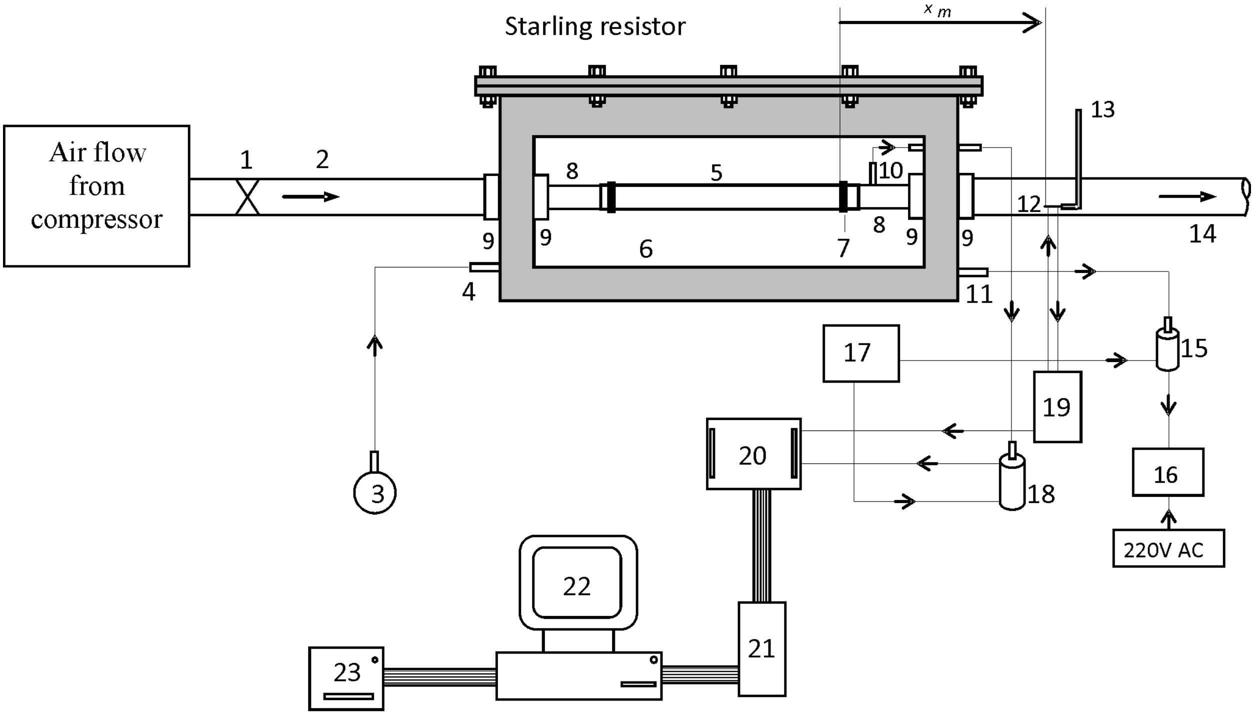
to investigate the possibility of the mean flow velocity determination for oscillating flows in pipes with the utilization of a hot wire anemometer. The position of the hot-wire probe corresponding to the mean oscillating velocity has been determined with respect to the measured data. The result is checked for a variety of test conditions and suggested location of the probe is seen to be nearly the same for the covered cases.

2. Experimental set-up and measurements

The open-system experimental set-up in which air is used as flowing fluid is shown schematically in Figure 1. Airflow is supplied from a screw type compressor which provides air in proportion to the consumption. Airflow is thereby steadily provided under a constant head at any desired flow rate. The test system is mainly composed of an airtight box, a collapsible tube and rigid pipes before and after the airtight box which is widely known as also "Starling resistor".

A collapsible tube which is mounted on rigid attachments with clamps at its ends has been placed horizontally in the Starling resistor. The pressure external to the collapsible tube (p_e) can be applied by a manual air pump. The rigid pipes before and after the Starling resistor are 2 meters long and they have an inside diameter of 25.4 mm. The steady flow entering to the test section is therefore maintained as fully developed. The volume of the airtight box is large enough for p_e not to be affected by the self-excited oscillations. The top cover of the box can be removed and closed in order to carry out experiments with different collapsible tubes. The inside diameter of the rigid attachment represented with part-8 in Figure 1 is 25.4 mm and the three different lengths of it are 17.5 mm, 47 mm and 79 mm. More detailed information regarding the set-up was presented in [10].

The undeformed inside diameter (D_o) of the tubes are 25.4 mm. The thickness of silicone rubber tubes are 1 mm, 2 mm and that of penrose tube is 0.55 mm. The length of the collapsible tube (L) was adjusted as the distance between two rigid attachments to enable that there was no any pretension loaded to the tube. According to the length of the rigid pipe segment, the tubes can be tested with different dimensionless ratios of L / D_o. For



1. Pressure regulator / regulator pritiska
2. Rigid pipe / kruta cijev
3. Manual air pump / ručna pumpa zraka
4. Valve for pressurizing the Staling resistor / ventil za presurizaciju Starling-ovog otpornika
5. Elastic tube / elastična cijev
6. Observation window / prozor za promatranje
7. Clamps / stege
8. Rigid attachments / kruti priključci
9. Connection parts with O-ring / spojni dijelovi s O-prstenom
10. Tapping for measuring p_2 / priključak za mjerenje p_2
11. Tapping for measuring p_e /priključak za mjerenje p_e
12. 55P14 Probe-Dantec / mjerna sonda 55P14 Dantec
13. Traverse mechanism / traverza
14. Rigid pipe / kruta cijev
15. Pressure transmitter / pretvarač signala tlaka
16. Digital process controller / digitalni procesni kontroler
17. DC power supply / izvor istosmjerne struje
18. Pressure transducer / transduktor tlaka
19. CTA 56C01-Dantec / CTA 56C01-Dantec
20. Screw terminal accessory bord / ploča za dodatke
21. DAS-1602 Hardware bord / DAS-1602 oprema za akviziciju podataka
22. Computer / računalo
23. Printer / pisač

Figure 1. A schematic representation of the experimental set-up together with its data acquisition and measurement system

Slika 1. Shematski prikaz eksperimentalnog aparata sa sustavom za mjerenje i akvizicijom podataka

instance if it is 17.5 mm, this ratio will be 10, while $L / D_o = 5$ for the case of 79 mm long rigid pipe segment. The latex (Penrose) and silicone rubber test tubes (without applying p_e) were placed in the centre of the Starling resistor with no longitudinal tension. The specifications of the test tubes are given in Table 1 together with the proposed tube coding system.

The measurement of p_e was carried out by means of a pressure transmitter in combination with digital processor controller at sensitivity of ±7 Pa. The pressure downstream of the test tube at $x_m = 0.7\ D_o$ was measured by means of a pressure transducer at a sensitivity of ±10 Pa. The time dependent velocity was measured on the rigid pipe at a distance of $2.45D_o$ from the exit of Starling resistor by means of the hot wire anemometer in combination with its miniature wire probe having a sensitivity of ±0.05 m/s. The hot wire probe was moved in the radial direction by means of a traverse mechanism with a dimensional sensitivity of ±0.25 mm. The probe was traversed at equal intervals covering the radial positions of $r = \pm 12$ mm, ±9 mm, ±6 mm, ±3 mm and $r = 0$ mm. A matter that arises when calibrating hot-wire anemometers is the correlation between the effective cooling velocity U_e, and the voltage across the hot wire, V_A. The most acceptable relationship defining this correlation is the King's Law defined as

$$(V_A)^2 = A + B(U_e)^n, \tag{1}$$

where A, B and n are constants. The exponent n usually varies from 0.4 to 1.3 and is stated to be strongly

Table 1. Properties of the test tubes

Tablica 1. Svojstva cijevi na kojima su vršena mjerenja

Material / Materijal	Tube Code / Oznaka cijevi	L, mm	D_o, mm	h, mm	Classification / Klasifikacija	Velocity Measurement station / Mjerna točka za mjerenje brzine, x_m
Penrose Tube / Lateks (Penrose drenažna cijev)	P_S	127	25.4	0.55	thin-walled	$7.56D_o$
	P_L	254	25.4	0.55	thin-walled	$5.12D_o$
Silicone Rubber / Silikonska guma	$S_{1,M}$	190.5	25.4	1	thin-walled	$6.30D_o$
	$S_{1,L}$	254	25.4	1	thin-walled	$5.12D_o$
	$S_{2,L}$	254	25.4	2	thick-walled	$5.12D_o$

dependent on the velocity regime [11]. The calibration of the probe in terms of U_e and V_A (Figure 2) yields for the three constants appear in King's Law as $A = 2.364$, $B = 0.996$ and $n = 0.456$, so that the following relationship was obtained in accordance with Eq. (1):

$$(V_A)^2 = 2.364 + 0.996(U_e)^{0.456}. \tag{2}$$

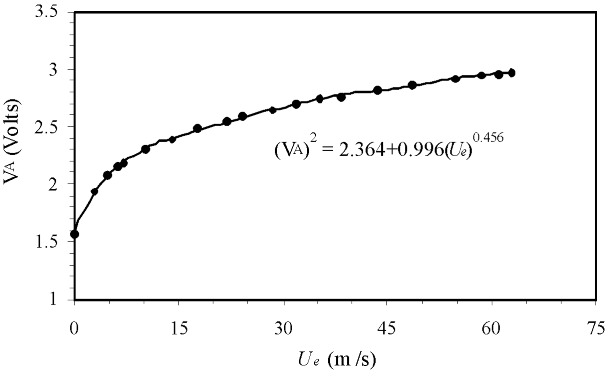


Figure 2. Calibration curve of hot-wire's probe

Slike 2. Kalibracijska krivulja mjerne sonde

The output voltages from CTA and pressure transducers were simultaneously acquired by the data acquisition system composed of an A/D converter installed in the computer via screw terminal accessory board. According to the well-known Nyquist theorem, the sampling rate must be equal to or greater than, twice the highest frequency component in the analog signal. Therefore the data-sampling rate was used as varying between 120 sample/second and 250 sample/second by the written data accumulation program corresponding to $f \leq 30$ Hz and $f = 100$ Hz, respectively so that the settled sampling rate value was high enough to satisfy the Nyquist's theorem. The stored velocity and pressure data were processed to obtain the Fast Fourier Transform (FFT) of the signals. The measurement station of the hot wire probe was at $x_m = 5.12D_o$, $6.30D_o$ and $7.56D_o$ from the end of the collapsible tubes $S_{2,L}$, $S_{1,M}$, and P_S respectively.

The measurements were conducted in a flow Re range of $7{,}000 \leq \text{Re} \leq 94{,}000$ ($\text{Re} = \bar{u}D_o/\upsilon$, where $\bar{u}$ is the mean flow velocity before collapse in undeformed tube and υ is the kinematic viscosity of air). A Pitot tube at $6D_o$ before inlet of the Starling resistor is used in collaboration with an inclined alcohol manometer having a sensitivity of ±10 Pa. Since alcohol level in the manometer's leg directly points out the dynamic pressure that is difference between total pressure measured from the Pitot tube and static pressure measured from rigid pipe wall, mean flow speed $\bar{u}$ is calculated from dynamic pressure. At the measurement station (x_m in Figure 1) the persistence of oscillations in the covered range of the experimental cases were checked and the ensemble averaged values of oscillating velocity based on instantaneous velocity data at each radial position, $u_{os}(r)$ were defined as:

$$u_{os}(r) = \frac{1}{N}\sum_{i=1}^{N} u_i, \tag{3}$$

where N is the number of data. The cross sectional mean oscillating velocity, $\bar{u}_{os}$ was later evaluated by numerical integration of $u_{os}(r)$ over the pipe cross section using the following equality:

$$\bar{u}_{os} = \frac{\int_0^{R'} 2\pi r u_{os}(r)dr}{\pi R'^2}, \tag{4}$$

where R' was the limiting position ($r = 12.0$ mm) of the hot-wire probe close to the wall.

3. Results and discussion

The flow inside the test tubes without an application of p_e was determined in terms of an experimental study providing also the calibration of the installed set-up and its coupled data acquisition system. The cross-sectional velocity distribution downstream of the test tubes in case of steady flow for a range of Re were appropriate with the well-known velocity profiles that can be seen from the sample plots of Figure 3 and Figure 4, respectively. The test cases with the application of p_e were found to be in two classes of which collapse of the test tube followed by oscillations called as oscillating and collapse without oscillations called as non-oscillating flows [12]. The ranges of p_e resulting in non-oscillating flow with collapse in the test tubes are given in Table 2. The experimental data obtained at $x_m = 5.12D_o$ is given in Table 3 such that the frequency band of the oscillations was between 13.94 Hz and 107 Hz for the study. It is clearly observed by referring Table 3 that instead of Re, the magnitude of p_e governed the formation of oscillations which were found to be severely dependent on the material properties of the test tube. This can be verified by examining Table 3 that f = 20 Hz for Re = 71,000 at p_e = 2.31 kPa and also for Re = 94,000 at p_e = 2.55 kPa in the experiment with $S_{1,L}$ tube. Namely, although Re changed noticeably and p_e slightly increases, f nearly remains constant. However, frequency increases dramatically to 107 Hz for Re = 80,000 when p_e = 13.92 kPa with the same tube. Therefore it can be concluded that f increases with p_e and it is much affected due to p_e rather than Re. In the oscillating cases visually observed collapse generated oscillations those directly affect velocity and pressure signals recorded downstream of the collapse as can be seen from the sample plots presented with Figure 5 and Figure 6.

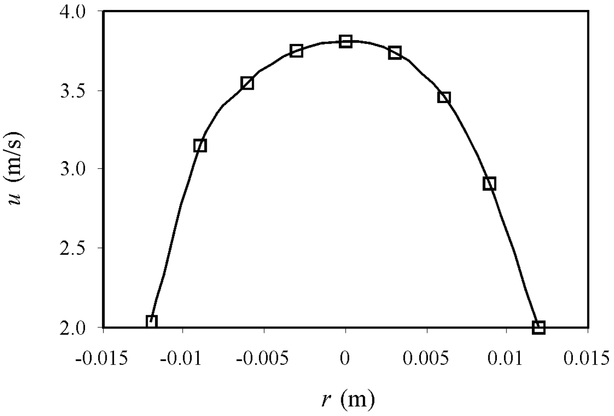


Figure 3. Cross-sectional velocity distribution downstream of $S_{1,L}$ in steady flow at $x_m = 5.12D_o$, Re = 5,300 with $p_e = 0$

Slika 3. Raspodjela brzine po poprečnom presjeku cijevi nizstrujno od $S_{1,L}$ pri stacionarnom toku na $x_m = 5.12D_o$, Re = 5,300 sa $p_e = 0$

Fast Fourier Transformation of the velocity signal, u for a steady case given for P_L (Figure 7) indicated that the Fourier spectrum has a variation between 0 and 0.28 in a frequency band of 0-60 Hz without oscillations. However when the oscillations were generated for the same case with an application of p_e as can be seen from Figure 8 Fourier spectrum of u_{os} indicated a dominant frequency of 18.16 Hz corresponding to a magnitude of 7.81.

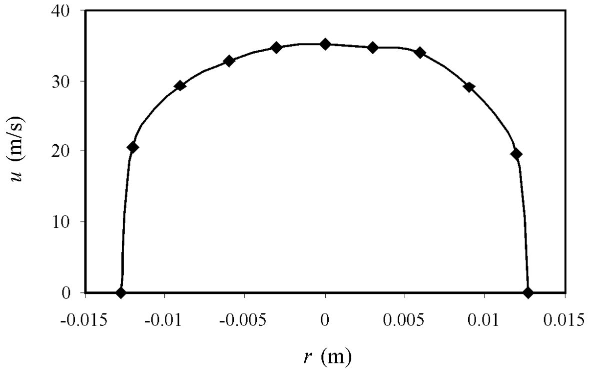


Figure 4. Cross-sectional velocity distribution downstream of $S_{1,L}$ in steady flow at $x_m = 5.12D_o$, Re = 51,000 with $p_e = 0$

Slika 4. Raspodjela brzine po poprečnom presjeku cijevi nizstrujno od $S_{1,L}$ pri stacionarnom toku na $x_m = 5.12D_o$, Re = 51,000 sa $p_e = 0$

Table 2. Ranges of p_e resulting in non-oscillating flow

Tablica 2. Rasponi pe koji rezultiraju ne-oscilirajućim tokom

Tube Code / Oznaka cijevi	Re	p_e, kPa
P_L	7,000	0
$S_{1,L}$	6,200	0 to 2.55
$S_{2,L}$	7,500	0 to 13.79

Table 3. Experimental data recorded at $x_m = 5.12D_o$

Tablica 3. Izmjereni podaci na $x_m = 5.12D_o$

Tube Code / Oznaka cijevi	Re (before collapse)	p_e, kPa	f, Hz
P_L	7,000	0.241	13.94
P_L	9,400	0.241	15.37
P_L	18,500	0.172	18.16
$S_{1,L}$	71,000	2.31	20.15
$S_{1,L}$	94,000	2.55	20.02
$S_{1,L}$	80,000	13.92	107.09
$S_{2,L}$	67,000	8.82	30.52
$S_{2,L}$	77,000	8.20	27.62

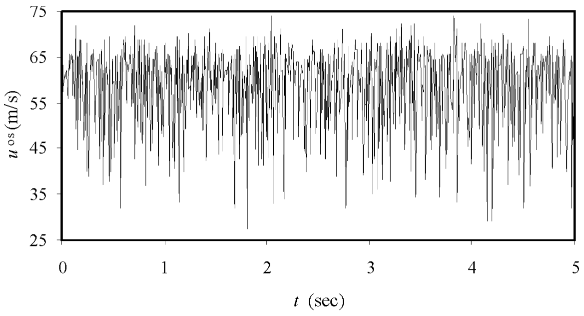


Figure 5. Variation of u_{os} with time at $r = 0$ and $x_m = 5.12D_o$ for $S_{2,L}$ tube under p_e = 8.62 kPa at Re = 84,000 with a sampling rate of 120 sample/second

Slika 5. Promjena u_{os} u vremenu na $r = 0$ i $x_m = 5.12D_o$ za $S_{2,L}$ cijev pri p_e = 8.62 kPa i Re=84000, sa brzinom uzorkovanja od 120 uzoraka/sekundi

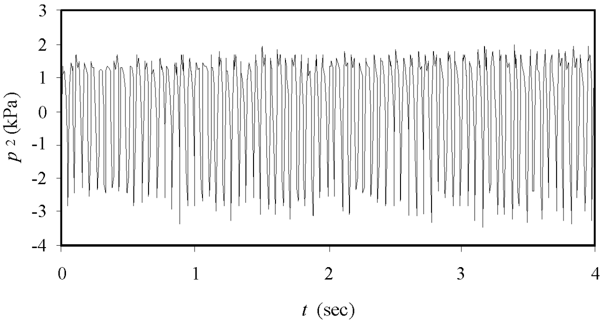


Figure 6. Variation of p_2 with time for P_L tube under $p_e = 0.17$ kPa at Re = 18,500 with a sampling rate of 120 sample/second

Slika 6. Promjena p_2 u vremenu za P_L cijev pri $p_e = 0.17$ kPa i Re=18500, sa brzinom uzorkovanja od 120 uzoraka/sekundi

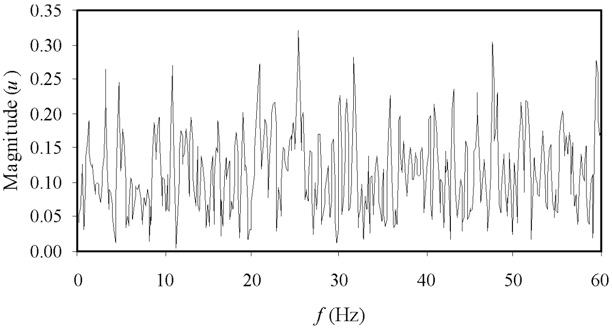


Figure 7. FFT obtained from u for P_L at $r = 0.755R$, $x_m = 5.12D_o$, $p_e = 0$ and Re = 18,500 (steady case)

Slika 7. FFT dobiven iz u za P_L cijev na $r = 0.755R$, $x_m = 5.12D_o$, $p_e = 0$ i Re=18500 (stacionarni slučaj)

Meanwhile the FFT of u for steady case was confined to a region shown by the dashed lines. Similarly the FFT of the pressure signal taken at the same condition given in Figure 9 confirmed the same frequency value for the oscillations as shown in Figure 8.

The cross sectional distribution of the ensembled average oscillating velocity data at the measurement station for the covered cases with the tubes $S_{1,M}$, $S_{2,L}$ and P_S in a range of $7{,}000 \leq \mathrm{Re} \leq 94{,}000$ indicated almost symmetrical velocity profiles with respect to the pipe centreline. The stated expression can be seen from the sample plot of Figure 10 independent of frequency and the distance from the collapse position of the test tube. The velocity profiles of $u_{os}(r)$ for the covered test cases were approximated in the form of the well-known power law expressions given in Table 4:

$$\frac{u_{\mathrm{os}}(r)}{u_{\mathrm{os,max}}} = \left(1 - \frac{r}{R}\right)^{1/c}, \tag{5}$$

where $u_{\mathrm{os,max}}$ is the maximum value of the oscillating flow velocity measured at pipe centre, r is radial position from the pipe centre, R is the pipe radius ($R = D_o/2$) and c is a constant of the power law. The numerical integration of the power law equations in Table 4 according to the definition of Eq. (4) resulted in the calculation of the mean velocity $\overline{u}_{os}$ in the field of self-excited oscillations. It is seen from Table 4 that the constant c present in Eq. (5) has a range of $5 < c < 7$ and the maximum oscillating velocity takes magnitudes as 12.5 m/s $< u_{\mathrm{os,max}} <$ 59 m/s. The position of the hot wire probe corresponding to $\overline{u}_{os}$ was determined to be between 0.750 R and 0.758 R which can be approximated as 0.755 R for the covered cases.

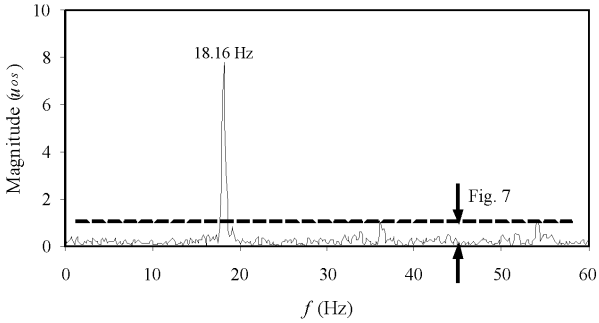


Figure 8. FFT obtained from $u_{os}(t)$ for P_L at $r = 0.755R$, $x_m = 5.12D_o$, $p_e = 0.17$ kPa and Re = 18,500 (oscillating case)

Slika 8. FFT dobiven iz $u_{os}(t)$ za P_L cijev na $r = 0.755R$, $x_m = 5.12D_o$, $p_e = 0.17$ kPa i Re=18500 (oscilirajući slučaj)

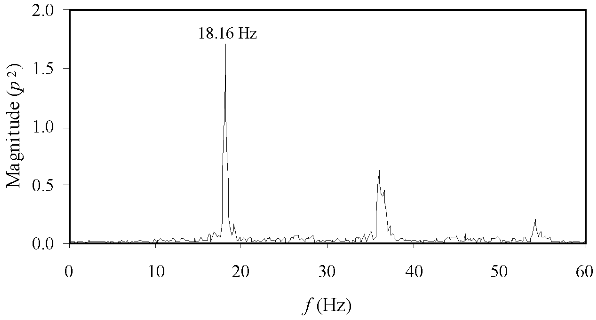


Figure 9. FFT obtained from $p_2(t)$ for P_L at $x_m = 0.7D_o$, $p_e = 0.17$ kPa and Re = 18,500 (oscillating case)

Slika 9. FFT dobiven iz $p_2(t)$ za P_L cijev na $x_m = 0.7D_o$, $p_e = 0.17$ kPa i Re=18500 (oscilirajući slučaj)

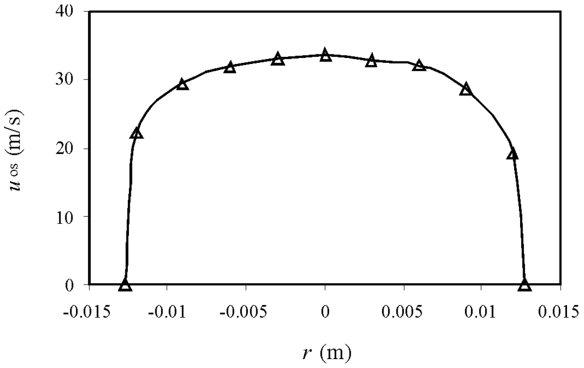


Figure 10. Velocity distribution downstream of $S_{1,M}$ in oscillating flow at $x_m = 6.3D_o$, Re = 61,000

Slika 10. Raspodjela brzine po poprečnom presjeku cijevi nizstrujno od $S_{1,M}$ pri oscilirajućem toku na $x_m = 6.3D_o$, Re = 61000

Table 4. Expressions for velocity profiles and position of hot wire probe corresponding to $\bar{u}_{os}$

Tablica 4. Izrazi za profile brzina i pozicije mjerne sonde u odnosu na $\bar{u}_{os}$

Tube Code / Oznaka cijevi	Re	Sample/sec / Uzorak / s	Power law expressions for $u_{os}(r)$ / Izraz potencijalne funkcije za $u_{os}(r)$	$\bar{u}_{os}$, m/s	Probe position corresponding to $\bar{u}_{os}$ / Pozicija mjerne sonde u odnosu na $\bar{u}_{os}$, (r, mm)	r/R corresponding to $\bar{u}_{os}$ / r/R u odnosu na $\bar{u}_{os}$
$S_{1,M}$	34,400	120	$22.60\left(1-\frac{r}{R}\right)^{1/5.01}$	17.13	9.53	0.750
$S_{1,M}$	61,000	120	$33.58\left(1-\frac{r}{R}\right)^{1/5.87}$	26.44	9.58	0.754
$S_{2,L}$	52,000	170	$34.35\left(1-\frac{r}{R}\right)^{1/4.84}$	25.80	9.52	0.750
$S_{2,L}$	87,000	160	$58.89\left(1-\frac{r}{R}\right)^{1/6.60}$	47.54	9.61	0.757
P_S	20,800	178	$12.52\left(1-\frac{r}{R}\right)^{1/5.26}$	9.61	9.55	0.752
P_S	34,000	168	$19.33\left(1-\frac{r}{R}\right)^{1/6.13}$	15.37	9.59	0.755
P_S	56,000	170	$29.11\left(1-\frac{r}{R}\right)^{1/7.03}$	23.79	9.62	0.757

4. Conclusions

In this investigation an approach has been developed for the determination of mean velocity of unsteady flows in pipes. A measurement technique with the utilization of hot-wire anemometer in the field of self-excited oscillations downstream of a collapsible elastic tube was presented. The possibility of a position in the pipe's radial direction which corresponds to $\bar{u}_{os}$ was researched. The velocity distribution was obtained from separate locations in pipe cross-section by traversing the hot-wire probe. The performed experiments with the utilization of different collapsible tube types verified this inquiry for a wide range of Re. The position of the probe corresponding to $\bar{u}_{os}$ was found to be 0.755R. In the investigated ranges of Re and f, the velocity data taken at this position can also be used to determine the oscillating flow rate as a function of time providing a tool for oscillating flow rate measurement. It can thereby be stated that a hot-wire anemometer system may alternatively be utilized for the oscillating flows according to the method outlined in the present study.

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