STRUCTURAL RESPONSE OF A PIPELINE APPARATUS TO PULSATING FLOW AT RESONANCE AND NON-RESONANCE CONDITIONS

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ABSTRACT
A large-scale pipeline apparatus at Deltares, Delft, The Netherlands, has been used for acoustic resonance tests. The apparatus consisted of a constant-head tank, a horizontal 200-mm-diameter 49-m-long steel pipeline and an oscillating valve at its downstream end. In addition to standard instrumentation, two distinctive instruments have been used: hot-film wall-shear-stress sensors and a PIV set-up for measurement of velocity profiles. Pulsating flow tests have been performed with an average flow at Reynolds number 22,000. The frequency of oscillation varied between 1.5 Hz and 100 Hz. When one of the excitation frequencies met the liquid system’s natural frequency, the system went into resonance. Moreover, when one of the frequencies coincided with a structural natural frequency of the pipeline, the liquid-filled pipeline experienced fluid-structural resonance. Results of three distinctive runs (including a hydraulic resonance case with oscillating frequency f_{ex} = 5 Hz, a non-resonance case with f_{ex} = 10 Hz and a fluid-structural resonance case with f_{ex} = 12.5 (13) Hz) indicated that the axial pipe-wall vibrations for the fluid-structural resonance case are one order of magnitude higher than in the hydraulic resonance and non-resonance cases. In addition, excessive pipeline vibrations were clearly visible in the PIV images.

KEYWODS
Pulsating Pipe Flow, Flow-Induced Vibrations, Structural Vibrations, Resonance, Experiment.

1. INTRODUCTION

The prediction of flow-induced vibrations in hydropower plants at the stages of planning and refurbishment is an important task in view of safe operation and economic design [1]. Skin friction and consequential damping in unsteady pipe flows can significantly reduce the

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harmful effects of resonance. This fact has been addressed in our previous IAHR WG Meeting presentation in Lausanne (2013) [2]. From an engineering point of view it is important to avoid resonance and its excessive vibrations [3]. When one of the excitation frequencies meets the liquid system's natural frequency, it goes into the resonance. Moreover, when one of the frequencies coincides with a structural natural frequency of the pipeline, the liquid-filled pipeline experiences fluid-structural resonance. Experimental data for the validation of theoretical models of flow-induced vibrations with consideration of unsteady skin friction and associated phenomena are limited. A large-scale pipeline apparatus at Deltares, Delft, The Netherlands, has been used for unsteady friction and acoustic resonance tests [4], [5]. The apparatus consisted of a constant-head tank, a horizontal 200-mm-diameter 49-m-long steel pipeline and an oscillating valve at its downstream end. Pulsating flow tests have been performed with an average flow at Reynolds number 22,000. The frequency of oscillation varied between 1.5 Hz and 100 Hz. Results of three distinctive runs (including a hydraulic resonance case with oscillating frequency f_{ex} = 5 Hz, a non-resonance case with f_{ex} = 10 Hz and a fluid-structural resonance case with f_{ex} = 12.5 (13) Hz) are presented and discussed. In addition, the pipeline's axial vibrations are examined from PIV images.

2. TEST RIG LAYOUT AND INSTRUMENTATION

A large-scale pipeline apparatus, where large scale implies both large Reynolds numbers (up to 400,000) and industrial-size pipeline dimensions (internal diameter of 206 mm, length 49 m), has been used for a range of unsteady skin-friction experiments [4], [5]. Three types of transient turbulent flow have been investigated in the apparatus: (1) non-reversing accelerating & decelerating flow, (2) reversing accelerating & decelerating flow and (3) oscillatory (pulsating) flow (including resonance & water-hammer tests). In this paper the pulsating flow tests are analysed with an emphasis on the fluid and fluid-structural resonance. Results from our previous theoretical and experimental investigations are used in the interpretation of the measurements [5], [6], [7], [8].

The layout of the test rig for pulsating flow experiments is depicted in Fig. 1. The test section is a horizontal steel pipeline with a total length of 48.95 m, an inner diameter of 206 mm and a wall thickness of 5.9 mm. The horizontal steel pipeline is restrained against axial and transverse movements by 12 pipe saddle supports with strap (see Fig. 2). The test pipeline is connected to a water tower via a supply steel pipeline of 27.35 m equivalent length and 903 mm equivalent diameter. It includes a 1.6-m-long and 489-mm-diameter section, a 500-mm-diameter ball valve, a 1-m-long tapered section and a horizontal-vertical 24.75-m-long and 993-mm-diameter steel pipeline that leads to the elevated constant-head tank. A specially designed rotating valve that generates harmonically oscillating flow rates and pressures is attached to the downstream end of the pipeline.

It is a Svingen-type frequency-controlled rotating valve that has been used in the apparatus [9]. The valve consists of an end-flange with a sluice gate and a Teflon disc driven by a frequency-controlled electromotor (5 kW). The valve's 8 mm × 100 mm aperture is partially covered by a solid latch to control the average flow rate. The rotating disc controls the oscillatory flow component. The mean disc diameter is 526 mm; there are three sinusoidal periods on the disc periphery with an amplitude of 10 mm. The frequency of oscillation can be varied between 1.5 Hz and 100 Hz. With a constant-head upstream-end of 24.5 m, the flow rate amplitude is determined by the maximum opening of the sluice gate (240 mm^2 herein) and the amplitude of the disc (10 mm herein).

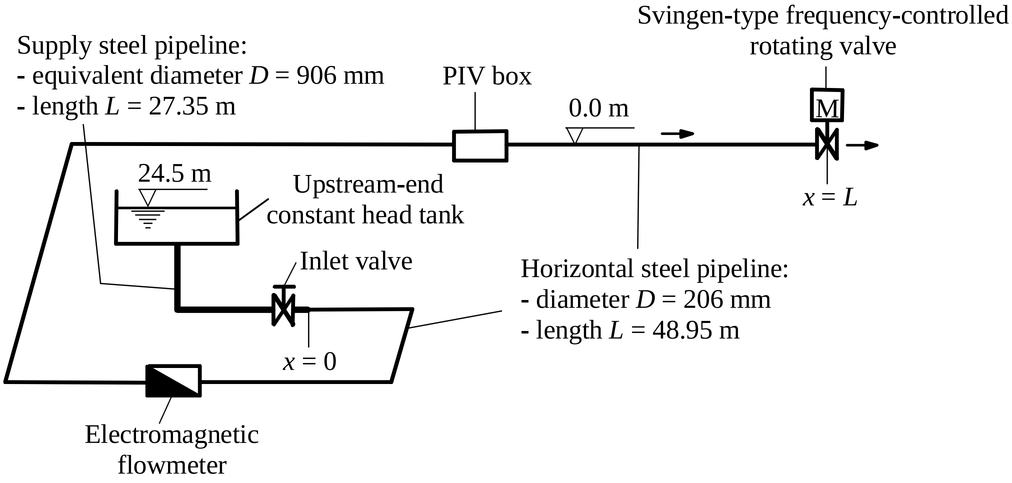

Fig.1 Test rig for oscillatory (pulsating) flow

In addition, water-hammer tests have been performed in the apparatus to determine the acoustic wave speed. For this purpose, a 25-mm-diameter ball valve was installed in the end-flange. With the sluice gate closed, the water-hammer event was initiated by rapid manual closure of the ball valve (N.B.: in the oscillating flow tests, the ball valve was fully closed). An additional 50-mm-diameter ball-valve in the end flange was used for removing air from the pipeline (by flushing) prior to the tests.

2.1 Instrumentation

The instruments used have been carefully selected (accuracy, frequency response, etc) and calibrated prior to and after the dynamic measurements. The sampling frequency for each continuously measured quantity (except PIV) was f_s = 1,000 Hz. The high-speed PIV camera was set to record at a lower frequency of f_s = 125 Hz to accommodate measured data for a time period of 10 seconds (resulting in large data files stored on hard-disc). The layout of the instruments in the test section for pulsating flow is depicted in Fig. 2. Four dynamic pressure transducers are positioned along the pipeline including the end points (p_u, p_{ov}), at the electromagnetic flow meter (p_{EM}), and at the PIV box (p_{PIV}). They are Kulite HKM-150-375M-50bar-A high-frequency piezoelectric absolute-pressure transducers (pressure range: from 0 to 5 MPa; resonant frequency: 50 kHz; uncertainty U_x = ±0.7% of rate). The uncertainty in a measured quantity (U_x) is expressed as a weighted sum of bias and precision errors [10]. All four transducers were flush mounted in the inner pipe wall. A fast-response DN200 ABB electromagnetic flowmeter (U_x = ±2% of flow rate) is used for flow-rate measurements (Q_{EM}) in steady and low-frequency pulsating flows. The flowmeter is located at 7/20 of the pipe length measured from the test-section inlet. The temperature (T_w) of the water in the pipe is measured at the flowmeter location using a Rosemount resistance thermometer (U_x = ±0.5 ^{o}C). A laser-Doppler displacement transducer ILD1401-250-mm is attached to the outer pipe-wall close to the PIV box. The transducer measures axial displacements (Y_x; U_x = ±0.02 mm).

Instantaneous velocity PIV measurements are carried out using a high-speed camera and a powerful laser for lighting (v_{PIV} in x (axial, horizontal) and y (radial, vertical) coordinate directions at selected positions across the window; estimated U_x = ±1%). The camera is adjusted so that it covers nearly the entire pipe radius (from the top of the pipe to the centre). The PIV box is located at 43/50 of the pipe length (measured from the inlet). The size of the window used is 512×1024 pixels. For high Reynolds-number flows, the laser is set to its maximum power. For lower Reynolds-number flows, the power is decreased. Hydrogen bubbles are used for seeding. They are produced by an electrified rod inserted in the flow at the upstream side as close as possible to the Perspex PIV box. One PC is dedicated to the PIV measurements using the special software DaVis 8.0. The wall shear-stress is measured at three equidistant circumferential positions by Dantec Dynamics hot-film sensors at two different axial locations. One location is at the PIV box ($\tau_{w,PIV}$) and the other is 1.15 m upstream. The hot-film sensors were calibrated against shear-stress values calculated from flow-rate and pressure-gradient measurements in steady flows [11].

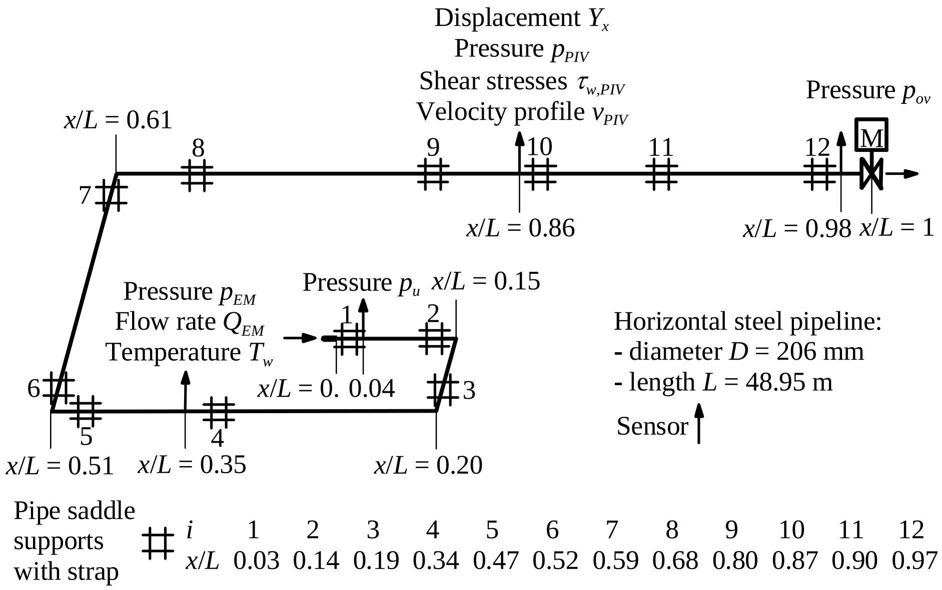

Fig.2 Layout of dynamic instruments in test section for oscillatory (pulsating) flow

2.2 Pulsating Flow Test Programme

The following pulsating flow tests have been performed in the test rig shown in Fig. 1:

(1) Quasi-steady tests (slowly rotating the disc by hand): $\mathbf{Re}_{ave}$ = 22,000
($\mathbf{Re}_{ave} = V_{ave}D/\nu$; V_{ave} = average flow velocity per cycle)

(2) Classical pulsating flow tests (valve rotating with frequencies between 1.5 Hz and 100 Hz; estimation of resonance frequencies; measurement of pipe motion): $\mathbf{Re}_{ave}$ = 22,000, which corresponds to V_{ave} = 0.108 m/s.

In the quasi-steady and pulsating flow tests the opening of the sluice gate varied between 80 mm^2 (minimum) and 240 mm^2 (maximum).

3. PULSATING FLOW TESTS AT RESONANCE AND NON-RESONANCE

Pulsating flow tests have been performed with an average flow at Reynolds number 22,000, which corresponds to V_{ave} = 0.108 m/s. The frequency of oscillation (f_{ex}) varied between 1.5 Hz and 100 Hz. Figure 3 shows pressure and axial displacement amplitudes measured at the PIV box versus the excitation frequency f_{ex} = 1.5 Hz to 25 Hz. Results for higher frequencies are not shown, because the PIV sampling frequency was f_s = 125 Hz. Two distinct resonance peaks are observed. The first resonance peak at f_{ex} = 5.0 Hz corresponds to the first natural frequency of the water column and is close to the theoretical value of 5.2 Hz [5]. The second distinctive peak at f = 13 Hz represents the first fluid-structural natural frequency. The first fluid-structural natural frequency is somehow close to the second theoretical hydraulic natural frequency f = 15.7 Hz and far below the theoretical first natural frequency f_s = 132 Hz of axial pipe motion of the downstream leg which has length $L_x = 0.39 \times L$ = 19 m. The simple formula $f_s = a_s / (2 L_x)$ with a_s = 5000 m/s for a free-free pipeline [3] has been applied thereby ignoring the effect of the supports 7 to 12. Because $f_s >> f$, the downstream leg acts as a rigid pipe (similar to the rigid-column / water-hammer analogy), the motion of which is restrained by the flexure of the leg between the support at x/L =0.52 and the bend at x/L = 0.61. This gives a lower structural frequency. The restraining effects of the supports 7 to 12, the last bend, the PIV box, and the blind flange and its attachments may all influence the first fluid-structural resonance frequency. It is hard to estimate dynamic behaviour of these components under fluid-structural resonance conditions.

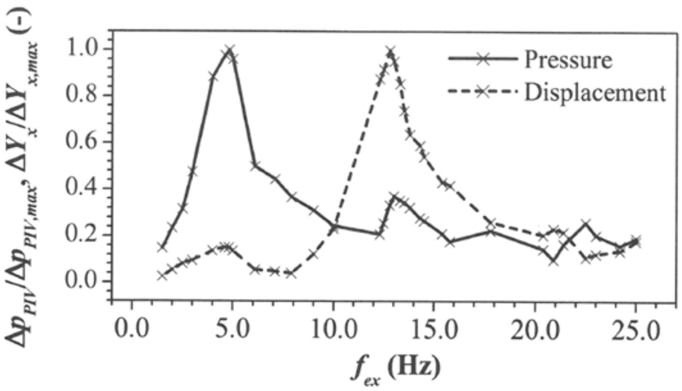

Fig. 3 Measured pressure and displacement amplitudes (normalised) at the PIV box versus frequency of oscillation of the rotating valve ($\Delta p_{PIV,max}$ = 0.9 bar; $\Delta Y_{x,max}$ = 0.7 mm)

Results of three distinctive runs including a hydraulic resonance case with f_{ex} = 5 Hz, a non-resonance case with f_{ex} = 10 Hz and a hydraulic resonance case with f_{ex} = 12.5 Hz (very close to the observed fluid-structural frequency f = 13 Hz) indicate that the wall shear-stresses at resonance conditions are about two times higher than at non-resonance conditions (Fig. 4f). The mode shapes of the first and the second hydraulic resonances can be estimated from the four pressure measurements along the pipeline (including the end points) (Figs. 4a to 4d). It is obvious that the maximum axial pipe displacement (Fig. 4e) occurs in the vicinity of the first fluid-structural resonance frequency (12.5 to 13 Hz). At these frequencies the whole system was shaking visually and audibly.

Large structural vibrations may affect the PIV measured flow velocities that have been presented at the previous IAHR meeting [2]. It has been shown that the shape of the velocity profile at non-resonance conditions is similar to the shape in steady-state flow. The shape of the velocity profile at resonance conditions was a typical unsteady-state velocity profile including pronounced decelerated flow and accelerated flow maxima near the pipe wall. In our PIV investigations the high-speed camera was at a fixed position while the pipeline was heavily vibrating at its first fluid-structural natural frequency f = 13 Hz. Therefore we have extracted the axial and radial pipeline displacements from the PIV images by tracking a selected mark fixed to the pipe wall itself and using it as a reference. Figure 5 shows axial and radial displacements of the selected wall mark for fluid-structure resonance (f_{ex} = 13 Hz) and non-resonance case (f_{ex} = 10 Hz). It is clear that the radial displacements are of the same order and small compared to the axial displacements. This is not the case for the axial displacements. While the axial displacement at non-resonance conditions is of the same order as the radial displacements, the axial-displacements at the first fluid-structural frequency are two to three times higher.

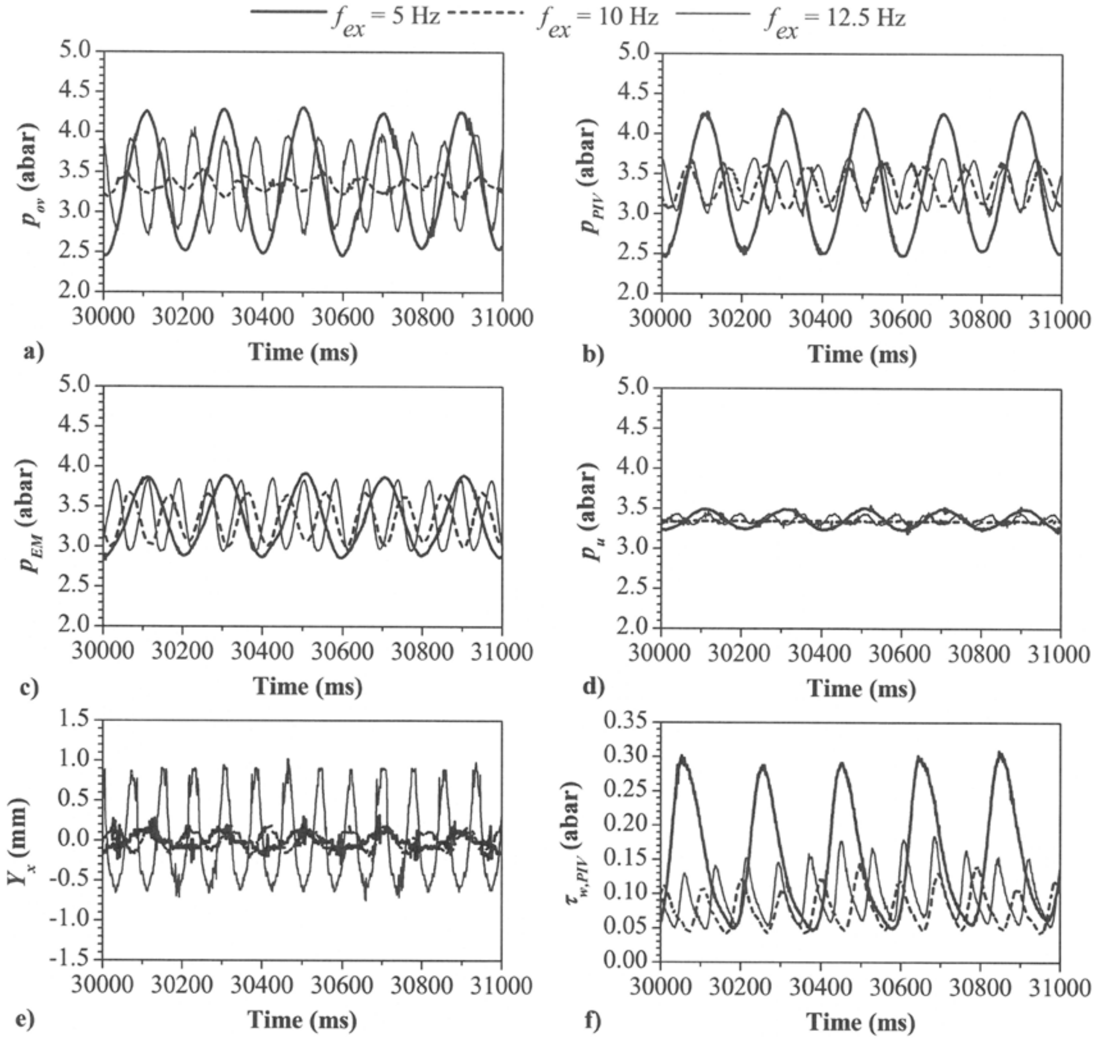

Fig. 4 Comparison of measured pressures along the horizontal test section (p, absolute), axial displacement at PIV box (Y_x) and wall shear stresses within the PIV box ($\tau_{w,PIV}$) for excitation frequencies f_{ex} = 5, 10 and 12.5 Hz

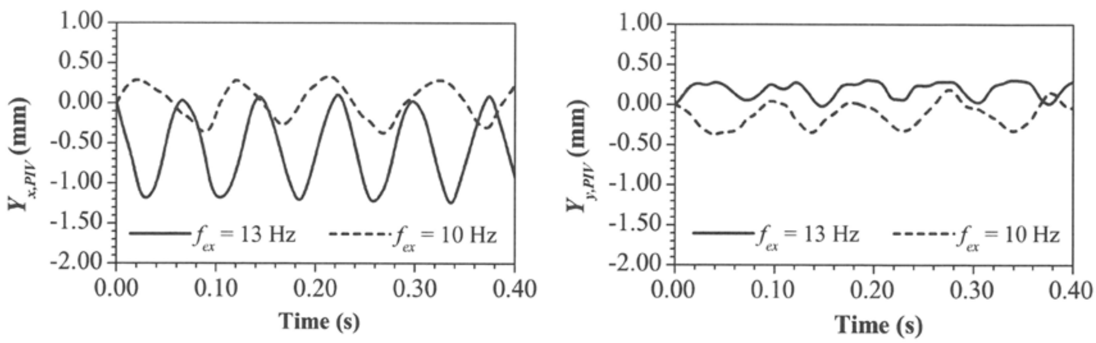

Fig. 5 Comparison of PIV images-based axial and radial displacements (Y) within the PIV box for excitation frequencies f_{ex} = 10 and 13 Hz

It has been found that the pipe wall velocity at the first fluid-structural natural frequency has an amplitude of about 0.05 m/s compared to an absolute (DC value) fluid velocity of about 0.07 m/s relative to v_{ave} (Figs. 6a and 6c). Pipe wall motion may therefore not be neglected in the treatment of the PIV measured flow velocity fields in the case of the first fluid-structural resonance. For the non-resonance case the axial wall and nearby fluid velocities are small. The amplitudes of the radial flow velocities (Figs. 6b and 6d) are much smaller than the axial amplitudes. This means that the fluid practically does not move in the radial direction. It is noted that the observed phase shift between the fluid flow velocities and displacements, and the pressures and wall shear stresses, is $\pi/2$ [5; Figs. 11 to 13].

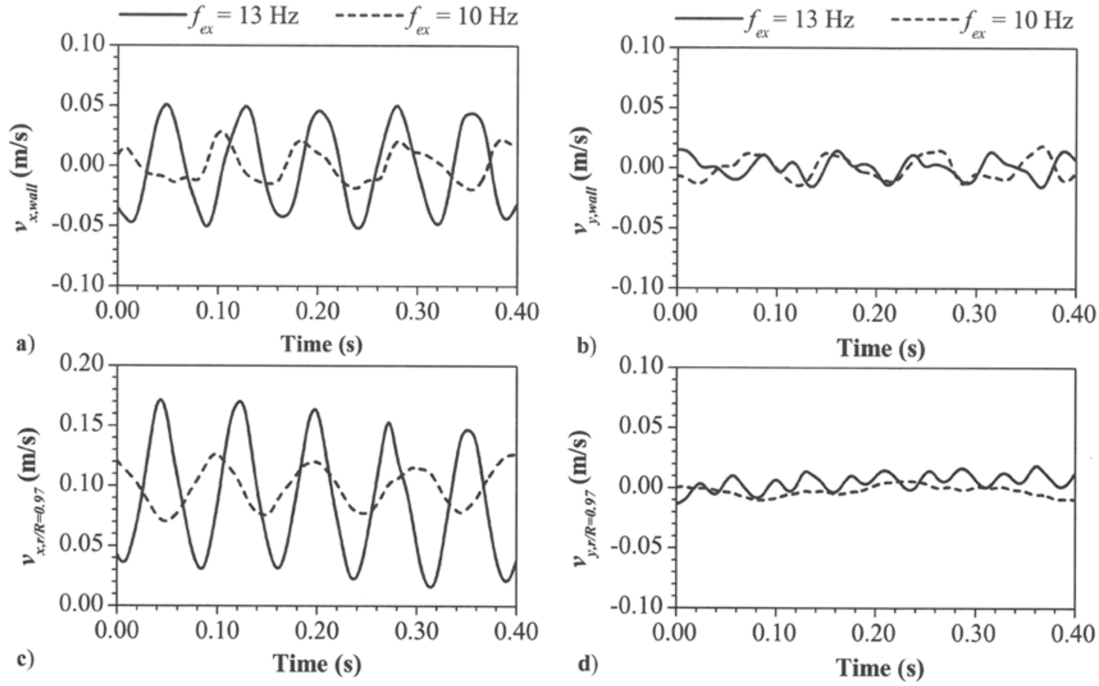

Fig. 6 Comparison of measured axial and radial velocities (v) of the pipe wall in the PIV box and of the flow velocities at r/R = 0.97 for excitation frequencies f_{ex} = 10 and 13 Hz

4. CONCLUSIONS

Results of three distinctive runs (including a hydraulic resonance case with frequency of oscillation f_{ex} = 5 Hz, a non-resonance case with f_{ex} = 10 Hz and a fluid-structural resonance case with f_{ex} = 12.5 (13) Hz) indicate that the axial pipe-wall vibrations in the fluid-structural resonance case are one order of magnitude higher than in the hydraulic resonance and non-resonance cases. The pipeline vibrations have herein been extracted from PIV images. The radial pipe-wall displacements at fluid-structural resonance are small and of the same order as under non-resonance conditions.

5. ACKNOWLEDGEMENTS

The large-scale laboratory experiments carried out at Deltares, Delft, The Netherlands, were partially funded through EC-HYDRALAB III Contract 022441 (R113) by the European Union and their support is gratefully acknowledged. In addition, the first two authors gratefully acknowledge the support of the Slovenian Research Agency (ARRS) conducted through the project L2-5491 (ARRS).

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7. NOMENCLATURE

a	(m/s)	wave speed	y	(m)	radial distance
D	(m)	pipe diameter	ν	(m^2/s)	kinematic viscosity
f	(Hz)	frequency	τ_w	(Pa)	wall shear stress
L	(m)	length	*Subscripts:*		
p	(Pa)	pressure	*ave*		average per cycle
Q	(m^3/s)	discharge	*EM*		electromagnetic flowmeter
Re	(-)	Reynolds number	*ex*		excitation
R	(m)	inner pipe radius	*max*		maximum
r	(m)	radial distance	*ov*		oscillating valve
T_w	(°C)	water temperature	*PIV*		particle image velocimetry
U_x	(any)	uncertainty	*s*		sampling, solid
V	(m/s)	average velocity	*u*		upstream
v	(m/s)	local flow velocity	*wall*		pipe wall
x	(m)	axial distance	*x*		axial direction
Y	(m)	pipe displacement	*y*		radial direction