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Experimental study of valveless pumping in a closed loop configuration

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Abstract: - The phenomenon of valveless pumping is studied in a ring consisting of two tubes, a flexible and a hard one filled with water. A non zero mean flow-rate is established via a reciprocating flat plate compressing and decompressing a portion of the flexible tube with a controllable frequency and depth of compression. Four parameters of the problem were examined, namely the frequency of the oscillating plate, its length, the depth of compression and the location where the tube is compressed. Four signals were simultaneously recorded, namely the flow-rate at the mid length of the hard tube, the static pressure at the tube's ends and the displacement of the oscillating plate. Also, the tube cross-sectional area was measured versus the displacement of the oscillating plate for various values of the maximum depth of compression. Analysis of the obtained data showed that a unidirectional flow is established increasing the frequency of compression and it maximizes when the compression frequency coincides with the natural frequency of the hydraulic loop. The mean value of the flow-rate increases when the point of compression moves far from the mid length of the flexible tube, when the length of the reciprocating plate increases and when the depth of compression increases. With regard to the direction of the flow this is from the area of the tube compression towards the end of the hard tube which is located closer to the compression area.

Keywords: -valveless pumping, unsteady flow, unidirectional flow, fluid-structure interaction

1 Introduction

The idea of valveless pumping was first introduced by observations of the human circulatory system in which blood flow in some pathological cases was due to the variable stiffness of the blood vessel walls. Long term studies of Liebau [1-3], a German physisian, ended up to this conclusion, giving an explanation for instance of the blood flow in patients with non operating heart valves or the blood flow in small diameter veins. Other cases in which blood flow exists without valves are met in the so called tunicates and amphioxus, small primitive animals which live in the sea and also in the circulatory system of the human fetus during the first weeks of the pregnancy. The most detailed experimental work published so far on this problem is that of Bredow [4] who used two water tanks at the same elevation connected through a flexible tube periodically compressed by a piston. Analytical and computational works have also appeared in the literature [5-7], without providing however solid conclusions about this complex fluid – structure interaction problem.

The present work was undertaken in order to shed more light in this area, by carefully preparing the experimental apparatus and using fast responding sensors for the detection of the flow characteristics.

2 Experimental set up

The experiments were carried out in a closed horizontal loop, filled with water, consisted of a flexible tube and a hard tube 1m long each, the hard tube made of Plexiglas (Fig.1).

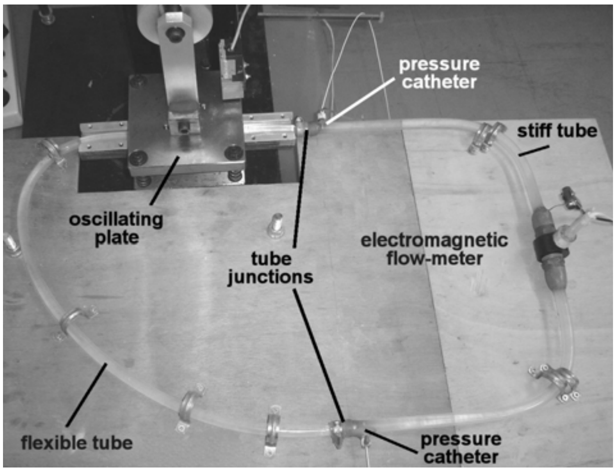


Fig.1 Hydraulic loop

The inner diameter of both tubes was 12mm and the thickness of the flexible tube was 1mm. A part of the flexible tube was periodically compressed and decompressed by a reciprocating flat plate with a controllable frequency (Fig.2).

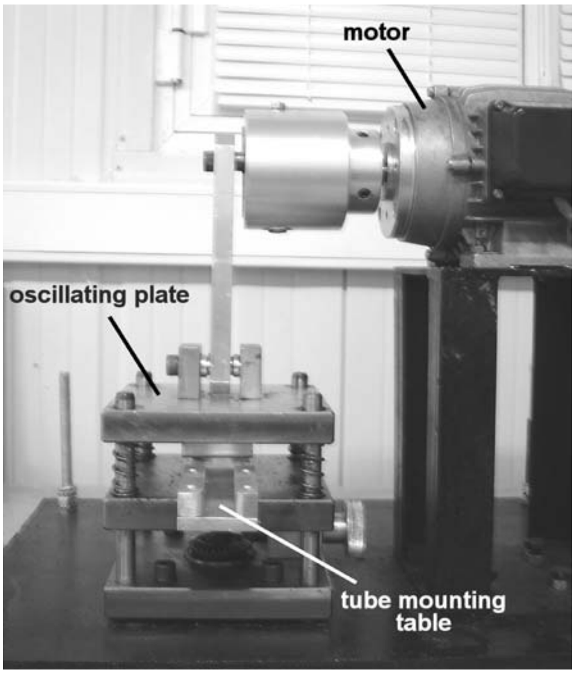


Fig.2 Oscillating plate

The static pressure was measured at the two ends of the hard tube using two piezoresistive transducers (Millar MPC-500) (Fig.1) whereas the flow-rate was measured at the mid length of this tube using an electromagnetic flow meter (Carolina F501) (Fig.1). The displacement of the oscillating plate was measured by a non contacting inductive sensor. The output of the above four sensors was recorded via a 16-bit A/D converter simultaneously as a function of time with a sampling frequency of 500Hz.

The examined parameters were: a) the frequency of the oscillating plate, (zero to 12Hz), b) the point of compression-decompression of the flexible tube (150mm, 330mm, 495mm, 500mm, 630mm, 850mm far from one end of the flexible tube), c) the length of the oscillating plate (60mm, 80mm, 100mm), and d) the depth of compression (the ratio of the minimum tube cross-sectional area to its original area).

3 Results and Discussion

The periodic compression and decompression of the flexible tube induces a pulsating flow, the mean flow-rate of which is non zero under certain conditions. The objective of the present work was to define these conditions of unidirectional flow examining the parameters mentioned in the previous paragraph. The mean flow-rate as well as the mean value of the other signals was based on 5000 samples which correspond to a total integration time of 10s, including a good number of periods since the examined compression frequencies were in the interval 1 to 12Hz. The frequency of oscillation was calculated by performing an FFT analysis of the sensor output which measured the displacement of the oscillating plate.

In order to accurately adjust the depth of compression, a mechanism was designed so that both the flexible tube mounting table could be moved in small steps up and down as well as the oscillating plate. Special care was taken so that the latter is parallel to the tube axis and as a consequence the compression is applied uniformly along the tube (Fig. 3).

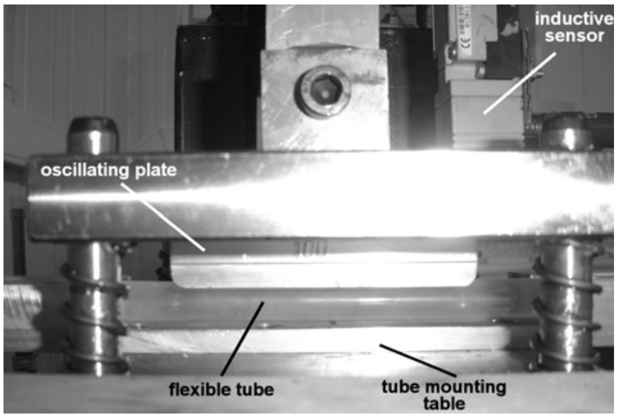
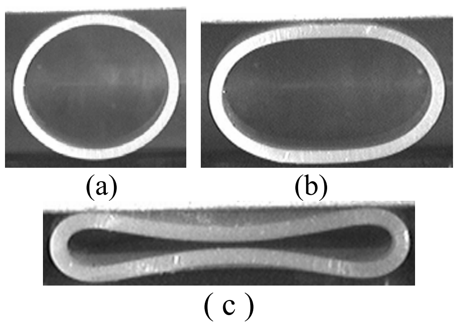


Fig.3 The oscillating plate and the flexible tube

The tube contraction ratio defined as $1\text{-}A_{mim}/A_0$, where A_{mim} is the minimum tube cross-sectional area and A_0 the original cross-section, was calculated as follows: using a short piece of the same flexible tube and a video camera, its cross-sectional area was recorded for various displacements of the oscillating plate (Fig.4).



(a) (b)

(c)

Fig.4 Undeformed (a), and deformed tube cross-sectional area (b, c)

The recorded images were then used to calculate the cross-sectional area A. An example of the variation of A with y (the displacement of the plate) is shown in Fig.5, when the plate moves downwards or upwards.

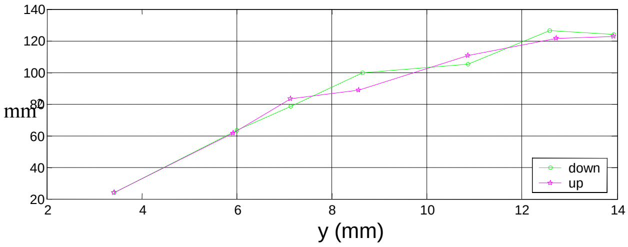


Fig.5 Tube cross-sectional area versus plate displacement

Based on this procedure, the following contraction ratios were examined in the present work: 81%, 70%, 68%, 61%, 49%, 45%, 38% and 36%.
Increasing the frequency of oscillation, the mean flow-rate increases up to a certain frequency and then it drops for all the examined cases. Since this was consistent, we assumed that the flow-rate peaks are due to a resonance phenomenon. Therefore, the natural frequency of the loop was measured by analysing the damped oscillatory fluid motion after an abrupt compression and decompression was applied to the flexible tube. An FFT analysis of the flow-rate signal (Fig. 6) showed that the frequency is 9.5Hz, that is within the area where the flow-rate maximizes.

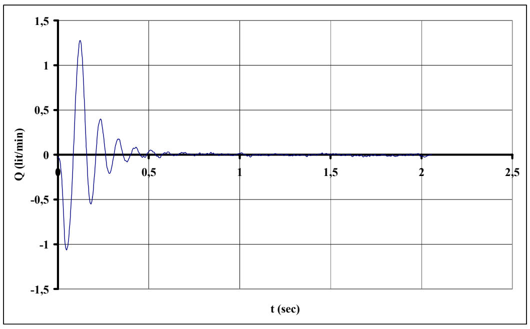


Fig.6 Flow-rate signal after an abrupt compression of the flexible tube

Characteristic curves of the mean flow-rate versus frequency are shown in Fig.7 for various contraction ratios. In this case the excitation of the tube takes place 150mm far from the stiff tube, and the plate is 100mm long.

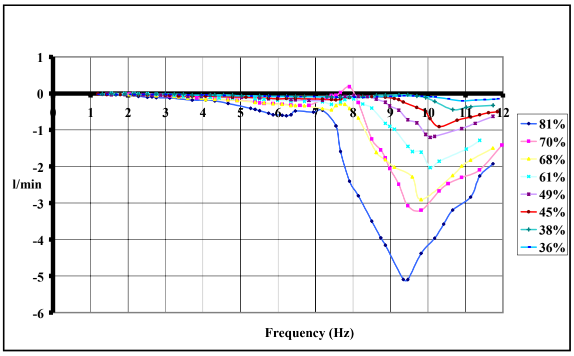


Fig.7 Mean flow-rate versus excitation frequency

Basic conclusions drawn from this figure are: a) there is no net flow for frequencies below 1Hz, b) for a given tube occlusion the flow-rate increases with a fast rate above 7Hz and after reaching a peak (between 9 and 11Hz) it tends to return to zero again, c) increasing the tube occlusion the curves are displaced to higher flow-rate values, d) the flow-rate peaks are shifted to lower frequencies when the tube occlusion increases. The negative sign of the flow-rate is an indication that the mean flow direction is from the excitation area towards the stiff tube end which is closer to the excitation area. It is also noticeable that for a 70% tube occlusion, flow-rate changes direction close to 8Hz presenting a local maximum. The appearance of local extremes of low values has been also documented by Bredow [4] as well as similar trends with the above conclusions using not a closed loop but a two open water tank experimental apparatus.
Increasing the length of the excitation area (length of the plate) the flow-rate increases as well, especially at frequencies where the flow-rate maximizes. At lower frequencies it is characteristic that the flow-rate is essentially independent of the length of the plate. This is clearly shown in Fig.8 for three lengths of the plate, 60mm, 80mm and 100mm.

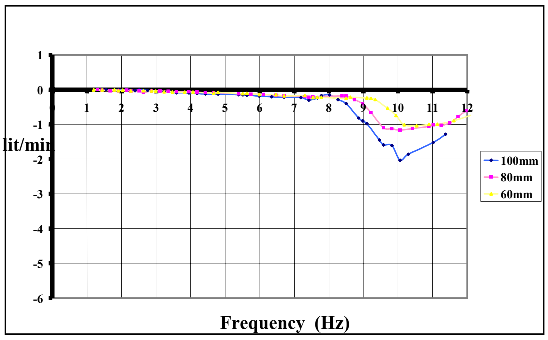


Fig.8 Flow-rate for various lengths of the oscillating plate

The flow direction changes when the point of excitation crosses the mid length of the flexible tube. However, careful experiments very close to the mid length point revealed that the mean flow-rate does not go to zero there. Namely, it seems that there is a sort of instability which turns the flow either to positive or negative without being zero. Fig.9 shows the mean flow-rate versus frequency for various points of excitation.

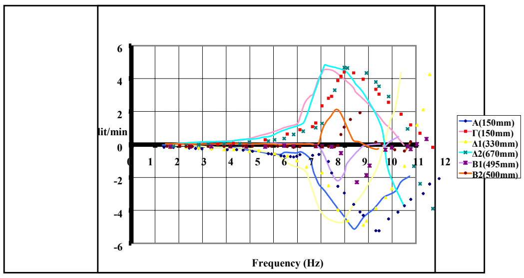


Fig.9 Flow-rate versus frequency for various points of excitation

What it is interesting to note is that when the excitation takes place 5mm close to the mid length point the flow-rate is negative (Fig.9, 495mm). When the excitation is 5mm further from this point, namely at the mid length point, the flow changes sign (Fig.9, 500mm). The positive mean flow-rate values of this graph correspond to excitation areas which are located at the other side of the mid length point, namely when the distances are greater than 500mm.

More details of this unsteady flow field can be revealed through the time series of the pressures at the edges of the stiff tube, the flow-rate and the inductive sensor's output. In Fig.10 these four signals are shown for two frequencies of excitation (at 150mm position), namely 9.46Hz and 11.73Hz. Also, the pressure difference Δp between the edges of the stiff tube along with the flow-rate are shown. The pressure which is located close to the excitation (p_1) is always in advance with respect to the pressure at the other end of the tube.

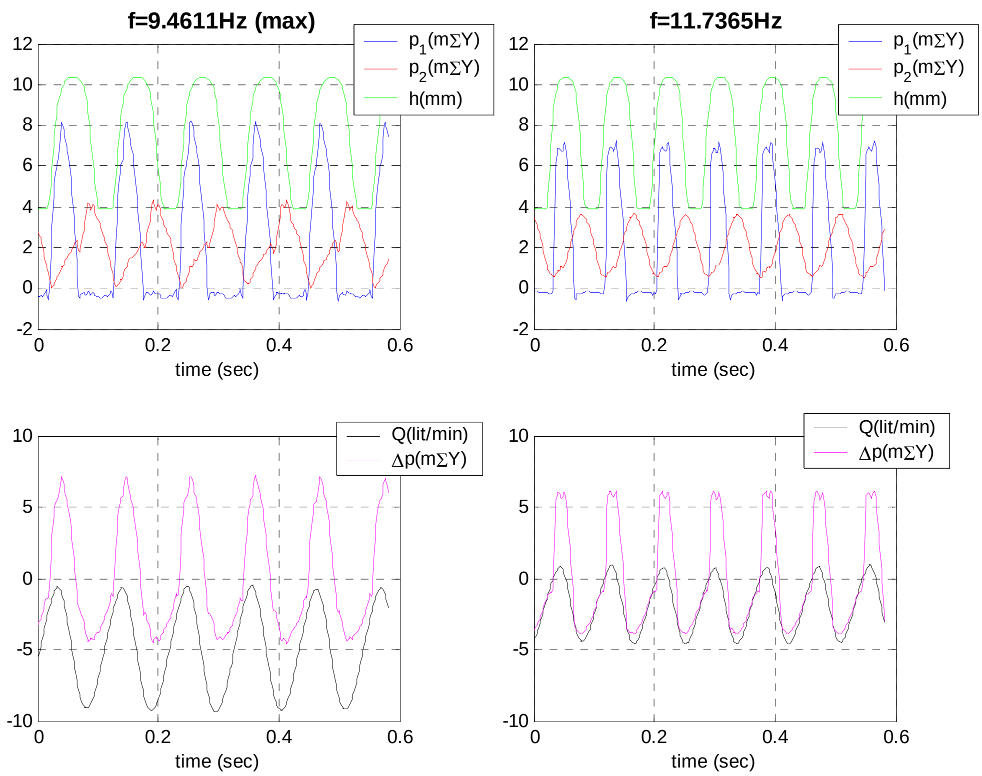


Fig.10 Pressure, flow-rate and displacement versus time

When the plate starts compressing the flexible tube, moving away from the stationary inductive sensor, the pressure (p_1), closer to the excitation area increases with a fast rate and returns to its initial value before the decompression has terminated. On the other hand, the pressure at the other end of the tube (p_2) starts increasing at a later instant with a phase lag of about 2π/3, following a small duration plateau for the case f=9.46Hz. Similar trends appear for the higher frequency of excitation (11.73Hz). A pressure difference (p_1 -p_2) is thus established which is in advance with respect to the flow-rate acceleration and deceleration. Namely, when the pressure difference changes sign the flow-rate reaches a peak after some delay, due to flow inertia. This phase difference between the two pressure signals is minimized when the excitation takes place at the mid length of the flexible tube. However, the mean flow-rate does exist in this case, being an interesting point for further research.

4 Conclusions

The flow in a closed horizontal loop consisted of a flexible tube and a stiff tube of equal lengths was examined, measuring the flow-rate at the middle of the stiff tube as well as the pressures at its two ends. Varying the frequency of the flexible tube compression and decompression, the mean flow-rate was found to maximize around 9Hz which was close to the natural frequency of the hydraulic loop. The mean flow-rate increased when a) the length of the compressed area increased, b) the point of compression was far from the mid point of the flexible tube, and c) the tube occlusion increased. The pressure signals presented a phase difference when the excitation is far from the mid length of the tube and minimizes at this point. The pressure at the point which is closer to the excitation is always in advance, increasing during compression with a faster rate compared to the pressure at the other end.

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