An Experimental Research Project on Sinusoidal Pulsatile Pipe Flows
Part 2: Influence of Oscillation Frequency and Amplitude on Onset of Transition to Turbulence

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Abstract: - Pulsatile air flow in the form of a sinusoidal wave generated inside a rigid pipe of diameter $D_1=26.6$ mm is the medium considered. The frequency and the velocity amplitude ratio, $f$ and $A_1$, are the major controlling parameters having the respective ranges of $0.1 \text{ Hz} \leq f \leq 14 \text{ Hz}$ and $0.05 \pm 0.0017 \leq A_1 \leq 0.96 \pm 0.03$. The generation and control of flow is described via development of instantaneous velocity waveforms and pressure signals along the axial direction. The overall flow nature is revealed based upon the measured cross-sectional velocity profiles at the measurement site. The covered range of oscillation parameters enabled an extended laminar flow range in comparison to the counterpart of steady air flow. The transition to turbulence is observed by the first turbulent bursts in the decelerating phase of the instantaneous velocity waveforms defined as the onset of transition. The experimental set-up, the coupled measurement and data acquisition system handling pressure and velocity signals in terms of a software program written in LabView 2009 SP1® are presented briefly. As an original contribution to the relevant literature, the critical time-averaged and oscillating Reynolds numbers at the onset of transition, $Re_{m,crit}$ and $Re_{os,crit}$ are expressed as a function of Womersley Number, $\sqrt{\omega}$ and velocity amplitude ratio, $A_1$.

Key-Words: - Onset of transition to turbulence, Womersley number, Velocity amplitude ratio, LabView.

1 Introduction
The experimental investigations on pulsatile pipe flows necessitate an accurate and safe measurement in terms of time-dependent data acquisition and analysis governed by the time-dependency of flow itself. In this paper, an experimental set-up which is used for the generation and control of pulsatile pipe flow with its combined measurement and data acquisition systems, the devised software program in LabView 2009SP1® environment are presented. Pulsatile flow generated by the superimposed of a sinusoidal oscillation on a steady flow counterpart is the medium considered. The interactive influence of the oscillation frequency, $f$ and velocity amplitude ratio, $A_1 = \left| \frac{U_{m,os,1}}{U_{m,nt}} \right|$ on nature of air flow in the cited frequency and amplitude ranges is revealed, where $U_{m,os,1}$ and $U_{m,nt}$ are the oscillating and time-averaged components of the cross-sectional mean velocity, respectively. The definitions and basic terminology used in pulsatile pipe flows can be found in the related literature [1-3]. Since the details of software program TDFC.vi devised in LabView 2009SP1® is the topic of the other paper of the authors in 3rd International Conference on Fluid Mechanics and Heat & Mass Transfer 2012, a simplified analysis on the collected data to determine the onset of transition to turbulence is introduced in this paper. The studies related to transitional pulsatile pipe flows in the literature are mainly based on the observations of velocity waveforms and the detection of disturbance growth. The first studies conducted on laminar to turbulent transition in a pulsatile pipe flow by means of flow visualization are ones given in [4-10]. Ohmi et al. (1982) classified the flows near the transition region into three types by means of the observation of velocity waveforms as; laminar, disturbed with small amplitude perturbation in the early acceleration phase of the velocity waveform and turbulent flow with turbulent bursts occurring in the decelerating phase and over the full oscillation cycle [11].
However, detection through the visual observations of velocity waveforms is a rather difficult method. The proposed software program for the detection of the onset of transition and the influences of the oscillation frequency and velocity amplitude ratio on the onset of transition to turbulence are presented herein.

2 Experimental Set-Up, Range of Study

The experimental set-up given in Fig. 1 is designed for generation, control and analysis of pulsatile flow with coupled measurement system [12].

The LKV 30/8 type of Lupamat screw air compressor is used to supply air flow. The compressor operates at 8 bar with a volumetric flow rate of 0.08 m$^3$/s. The mass flow control (MFC) unit [13] is used to generate controlled steady and time-dependent flow from a compressed air supply input up to oscillation frequencies of 125 Hz. The MFC unit provides 0 to 0.003 m$^3$/s flow rate with supplied compressed air pressure between 3 and 6 bar [13].

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The MFC unit is controlled automatically over an analog port (0 to 10 V). Smooth, rigid, polyvinyl chloride (PVC) pipe line of an inner diameter of 26.6 mm at a length of 17.4 m is used. A couple of pipe inserts in form of a tube bundle and a perforated plate placed at 12$D$ and 14$D$, respectively downstream of the MFC unit are used in order to have fully-developed flow at feasible lengths in the pipeline [14].

The cross-sectional velocity measurement is conducted at $X/D=604$ where the laminar flow is fully developed. DANTEC 56C01 constant temperature anemometer (CTA)-56C17 CTA bridge, the 56N21 linearizer with 55P11 general purpose type miniature hotwire probe, are used for the velocity measurement [15]. The probe traversing mechanism is composed of RCP2-SA6-1-PM-6-200-P1-SBE Robocylinder and RCP2-CGA-SA6-1-PM-0-P Robocylinder Positioning Unit to traverse the hotwire probe with a repeatability of 0.02 mm.

Local static pressures at 7 downstream locations are measured by WIKA SL-1 pressure transmitters having operating pressure ranges of ±20 mbar, response time of 1 µs, time resolution of 1 kHz, accuracy of <0.5%, linearity of <0.2%, repeatability of <0.1%.

A 16-bit, 1-MHz A/D converter IOtech Daq3001 USB board coupled to a PC is used to control MFC unit and to accumulate the instantaneous velocity and pressure signals. The IOtech Daq3001 USB board is set to take 6000 data
readings of local instantaneous speed $U = U(r,t)$ and local instantaneous static pressure $P = P(t)$ at a rate of 100 Hz. The sensibility of the devised program $TDFC.vi$ in LabView 2009SP1®, through the signal accumulation, from measurement chain can be expressed in terms of the calculated uncertainties in $U = U(r,t)$ and $P = P(t)$ which are ±2.1 % and ±1.3% respectively in the covered range of study. Meanwhile the uncertainties of the calculated time-averaged and oscillating components of the cross-sectional mean velocity, $\bar{U}_{m,ta}$, $|\bar{U}_{m,os}|$, and thereby time-averaged and oscillating Reynolds numbers, $Re_{ta}$ and $Re_{os}$ are found to be ±3.4%, whose definitions are given as follows;

$$Re_{ta} = \frac{\bar{U}_{m,ta} D}{\nu}$$  \hspace{1cm} (1)

$$Re_{os} = |\bar{U}_{m,os}| \frac{D}{\nu}$$  \hspace{1cm} (2)

where $D$ is the pipe diameter and $\nu$ is the kinematic viscosity of fluid.

The ranges of time-averaged Reynolds number, $Re_{ta}$; 1019±35≤$Re_{ta}$≤4817±64, oscillating Reynolds number, $Re_{os}$; 107±4≤$Re_{os}$≤4261±145, velocity amplitude ratio, $A_1$; 0.05±0.0017≤$A_1$≤0.96±0.03 and Womersley number, $\sqrt{\omega R}$ = $R\sqrt{\omega / \nu}$ (where $\omega$ is the angular frequency of oscillation, $\omega = 2\pi f$ and $R$ is the pipe radius); 2.72≤$\sqrt{\omega R}$≤32.21 are covered during the execution of 227 runs.

The overall system is compatible to conduct controlled runs-cases in which $Re_{ta}, Re_{os}, \sqrt{\omega R}$ and $A_1$ are changed systematically. The sample velocity waveforms at $X/D$ = 604 and the sample plot for the variation of static pressure along the axial direction corresponding to the onset of transition are given in Figs. 2 and 3.

In the covered range of study, flow of steady counterpart is laminar up to a determined critical limit of $Re = 2450$. Steady flow tends to turbulence with the magnitude of $Re$>2450. This limit–critical $Re$ is deduced through the cross-sectional velocity profiles measured at $X/D$ = 604. However inside sinusoidal air flow addition of an oscillation causes an extended range of laminar flow. Determination of the critical point as the onset of transition is therefore corresponding to the relevant critical magnitudes of $Re_{ta}$, $Re_{os}$. The onset of the transition is defined as the state where the first turbulent bursts/perturbations are seen in the velocity waveforms. The turbulent bursts are firstly seen in the decelerating phase of the velocity waveforms as can be observed from the sample plot in Fig. 4.

The turbulence detection method which is embedded in $TDFC.vi$ is used for the purpose [12]. Inside sinusoidal air flow the critical magnitudes of $Re_{ta}$ and $Re_{os}$ as $Re_{ta, crit}$ and $Re_{os, crit}$ at the onset of the transition are found to be greater than critical $Re$ of steady flow. The particular attention in the
presentation is given to the influence of $A_1$ and $\sqrt{\omega'}$ on $Re_{ta,crit}$ and $Re_{ts,crit}$.

3 Results and Discussion

3.1 Influence of $A_1$ and $\sqrt{\omega'}$ on $Re_{ta,crit}$

The influence of $A_1$ on $Re_{ta,crit}$ in the covered range of $\sqrt{\omega'}$ is given in Figs. 5a-5d. The variation of $Re_{ta,crit}$ with $A_1$ up to $\sqrt{\omega'} = 8.61$ ($f=1$ Hz) is completely different from that for $\sqrt{\omega'} > 8.61$. Since $Re_{ta,crit}$ does not vary with $A_1$ maintaining nearly a constant magnitude in the range between 2500-3000 for $\sqrt{\omega'} > 8.61$. Meanwhile the maximum $Re_{ta,crit}$ value are seen at $\sqrt{\omega'} = 3.85$ for which increase in $A_1$ is with an increase in $Re_{ta,crit}$. In fact influence of $A_1$ on $Re_{ta,crit}$ seems to be dependent on the magnitude of $\sqrt{\omega'}$ due to the strong influence of $A_1$ which is restricted to the cases with $\sqrt{\omega'} = 3.85$, $\sqrt{\omega'} = 5.44$, $\sqrt{\omega'} = 6.67$, $\sqrt{\omega'} = 7.70$. The increase in $\sqrt{\omega'}$ towards the estimated limiting value of 8.61 is also linked with decrease of the influence of $A_1$ on $Re_{ta,crit}$. Inside the covered range, transition to turbulence is delayed with a maximum $Re_{ta,crit} = 4817$ observed at $\sqrt{\omega'} = 3.85$.

![Graph](image1)

Fig. 5 Effect of $A_1$ on $Re_{ta,crit}$ in the Range of $2.72 \leq \sqrt{\omega'} \leq 32.21$

The influence of $\sqrt{\omega'}$ on $Re_{ta,crit}$ in the covered range of $A_1$ is given in Figs. 6a-6c. As a confirmation of the observations in Fig. 5, change in $\sqrt{\omega'}$ does not affect the values of $Re_{ta,crit}$ at $A_1 = 0.10$ and $A_1 = 0.20$. However for the other $A_1$ values, $Re_{ta,crit}$ value tends to increase up to $\sqrt{\omega'} = 3.85$ ($f=0.2$ Hz), then begins to decrease up to $\sqrt{\omega'} = 12.17$ and maintain nearly constant for $\sqrt{\omega'} > 12.17$.

![Graph](image2)
3.2 Influence of $A_1$ and $\sqrt{\omega'}$ on $\text{Re}_{\text{os,crit}}$

There is a linear relationship between $\text{Re}_{\text{os,crit}}$ and $A_1$ for the covered $\sqrt{\omega'}$ in conformity with the related definitions of $\text{Re}_{\text{os}}$ and $A_1$ (Fig. 7). The relationship between $A_1$ and $\text{Re}_{\text{os,crit}}$ for $\sqrt{\omega'} = 3.85$ is given with the dashed line with a mean deviation of $\pm4\%$ as follows:

$$\text{Re}_{\text{os,crit}} = 5088A_1 - 455 \quad (3)$$

The relationship between $A_1$ and $\text{Re}_{\text{os,crit}}$ for other magnitudes of $\sqrt{\omega'}$ except $\sqrt{\omega'} = 3.85$ is denoted with the straight line with a mean deviation of $\pm7\%$ as follows:

$$\text{Re}_{\text{os,crit}} = 3086A_1 - 46 \quad (4)$$

$\text{Re}_{\text{os,crit}}$ does not vary with $\sqrt{\omega'}$ at $A_1 = 0.10$ and $A_1 = 0.20$ as seen in Fig. 8. The values of $\text{Re}_{\text{os,crit}}$ are in the ranges of $\text{Re}_{\text{os,crit}} \approx 250$ for $A_1 = 0.10$ and $\text{Re}_{\text{os,crit}} \approx 500$ for $A_1 = 0.20$. Meanwhile for other $A_1$ values, $\text{Re}_{\text{os,crit}}$ value tends to increase up to $\sqrt{\omega'} = 3.85$ ($f = 0.2$ Hz), then begins to decrease up to $\sqrt{\omega'} = 12.17$ and maintain nearly constant after $\sqrt{\omega'} = 12.17$. Furthermore the magnitudes of $\text{Re}_{\text{os,crit}}$ increase with increase in $A_1$ as sensed with $\text{Re}_{\text{os,crit}} = 987$ at $A_1 = 0.30$ and $\text{Re}_{\text{os,crit}} = 4261$ at $A_1 = 0.90$ for $\sqrt{\omega'} = 3.85$. 

Fig. 7 Effect of $A_1$ on $\text{Re}_{\text{os,crit}}$ in the Range of $2.72 \leq \sqrt{\omega'} \leq 32.21$

Fig. 8 Effect of $\sqrt{\omega'}$ on $\text{Re}_{\text{os,crit}}$ in the Range of $0.10 \leq A_1 \leq 0.90$
4 Conclusion
The proposed method for the determination of the onset of transition provides ease when compared with the conventional method of visual observations of turbulent structures on velocity waveforms.

As an expected fact, the interactive influence of $\sqrt{\omega^2}$ and $A_i$ is apparent for sinusoidal flow in terms of $Re_{ta, crit}$ and $Re_{ox, crit}$ which are indicating a departure from a well-defined flow field into a non-linear transitional one. The critical magnitudes of $\sqrt{\omega^2}$ are seen to be $\sqrt{\omega^2} = 8.61$ and $\sqrt{\omega^2} = 12.17$. Since the behavior of the relationships of the searched parameters $Re_{ta, crit}$ and $Re_{ox, crit}$ indicate somehow strong differences corresponding to these critical magnitudes of $\sqrt{\omega^2}$. Almost no influence of $\sqrt{\omega^2}$ on $Re_{ta, crit}$ and $Re_{ox, crit}$ is seen for $\sqrt{\omega^2} > 12.17$.

The critical magnitudes of $A_i$ are observed to be $A_{i1} = 0.10$ and $A_{i2} = 0.20$ with no influence of $\sqrt{\omega^2}$ on $Re_{ox, crit}$. However, there is a strong influence of $\sqrt{\omega^2}$ on $Re_{ox, crit}$ at higher $A_i$ inside $\sqrt{\omega^2} < 12.17$.

It is also observed that the maximum $Re_{ta, crit}$ values are seen for $\sqrt{\omega^2} = 3.85$. The onset of transition is delayed up to $Re_{ta, crit} = 4817$ at $\sqrt{\omega^2} = 3.85$ in the covered ranges of the study.

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