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A new approach to investigate wave dissipation in viscoelastic tubes: application of Wave Intensity Analysis

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Abstract--**Wave dissipation in elastic and viscoelastic medium has been investigated extensively in the frequency domain. The aim of this study is to examine the pattern of wave dissipation in the time-domain using Wave Intensity Analysis. A single semi-sinusoidal pulse was generated in 8mm and 16mm diameter tubes; each is of 200cm in length. Pressure and flow measurements were taken at intervals of 5 cm along the tube. In order to examine the effect of the wall mechanical properties on wave dissipation, we also modified the wall of the 16mm tube; a thread of strong cotton was wound with a pitch of approximately 30° around the circumference of the tube in the longitudinal direction. The separated forward pressure, wave intensity and wave energy were calculated using Wave Intensity Analysis. The amplitudes of the forward pressure wave, wave intensity and wave energy dissipated exponentially with distance. In the 8mm diameter tube, the dissipation of forward pressure, wave intensity and wave energy were greater than those in 16mm tube. For the same sized of tube, there was no significant difference in the dissipation of forward pressure, wave intensity and wave energy between the modified and normal wall tubes. It is concluded that the size of tube has a significant effect on the wave dissipation but the mechanical properties of the wall do not have a discernable effect on wave dissipation.**

I. INTRODUCTION

OVER the past few decades wave propagation in blood vessels and viscoelastic tubes has been examined extensively. Anliker [1,2,3,4] examined the wave transmission characteristic in blood vessels in the frequency domain and found that wave dissipated exponentially with the distance travelled. Anliker [5] concluded that the damping of the various waves in any vessels may be attributed to the following possible mechanisms: (1) radiation into the surrounding tissue, (2) dissipation due to the viscosity of the blood and (3) the viscoelasticity of the vessel wall. Theoretical results have shown the viscosity to be of minor importance to wave dissipation. Anliker [4] also demonstrated that the radiation of surrounding medium has little effect on wave dissipation. It thus appears that the primary mechanism for wave dissipation is the viscoelasticity of the wall itself. Newman [6] also examined the pulse wave propagation in viscoelastic medium in the frequency domain experimentally and concluded that pulse wave amplitude attenuated along the travelling distance as monoexponential reduction function in the latex tube. However, conclusions from Ursino [7] and Bertram [8] had shown considerable disparity in the estimations of wave dissipation values, and different explanations about the reasons for this disparity have been suggested.

This study explores wave dissipation in the time domain using Wave Intensity Analysis [9], which is a relatively new method that proved useful in studying waves in the arterial system. The method has the advantage of not assuming any periodicity or linearity in the system. The method is also a time-domain analysis, which will enable us to study wave dissipation both in time and space.

The measured waves are the summation of the forward and the backward (reflected) waves which makes it more complicated to examine wave dissipation along a certain direction. Wave Intensity Analysis simplifies this problem by separating the measured wave into their forward and backward directions, and waves dissipation is then examined using the forward pressure instead of the measured pressure.

Furthermore, Wave Intensity Analysis makes it possible to examine wave dissipation in terms of energy. Herein we present the experimental result about wave energy dissipation along the travelled distance.

II. THEORETICAL BACKGROUND

Parker and Jones [9] introduced a method, to separate the pressure and velocity waveforms into their forward and backward directions. The theoretical work is based on the solution of the one-dimension equations of conservation of mass and momentum in elastic tubes, which are

$$A_t + (UA)_x = 0 \tag{1}$$

$$U_t + UU_x + \frac{P_x}{\rho} = 0 \tag{2}$$

Where P, U are pressure and velocity in the tube over the time *t*. *A* is cross-section area of tube, ρ is density and *x* is the wave travelled distance. The water hammer equation is

$$dP_{\pm} = \pm \rho c dU_{\pm} \tag{3}$$

Where $\pm$ denotes the forward and backward direction, $dP_{\pm}$ and $dU_{\pm}$ denote the forward and backward wavefronts of pressure and velocity, c is wave speed. Wave intensity, dI, which is the energy carried by the wave per cross-section area [10], is defined as the product of dP and dU, which can be expressed as:

$$dI = dPdU \tag{4}$$

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Where, dP and dU denote changes in the pressure, P and velocity U, respectively. The forward and backward pressure [12] can be calculated as

$$dP_{\pm} = \frac{1}{2}(dP \pm \rho c dU) \quad (5)$$

$$P_{+} = P_{0} + \sum dP_{+} \quad (6)$$

Where, P_0 and P_+ are initial static pressure and forward pressure respectively.

Separated wave intensity [11] can be calculated as

$$dI_{\pm} = \pm \frac{1}{4\rho c}(dP \pm \rho c dU)^2 \quad (7)$$

The wave intensity has a unit of W/m^2 and its integration, which we call 'wave energy', will have units of 'J/m^2'.

III. METHOD

A. Experiment setup

Wave dissipation was investigated experimentally with two sizes of latex tubes, 8mm and 16mm in diameter; each is of 200 cm in length (see Fig.1). A rectangular tank filled water, 50cm in width and 200cm in length, was used to support tubes. The inlet and outlet of the tank were connected with two small reservoirs, whose level can be adjusted to provide initial head. The level of water in the tank was just above the tube. This guaranteed a uniform transmural pressure and support of tube. A piston pump produced one forward semi-sinusoidal signal at the inlet of the tube. Pressure and flow were measured at 5cm intervals along the tubes. Ultrasound flow probes (Transonic System Inc, Itheca, NY, USA) were used to record flow rate and a strain gauge transducer tipped catheter (Gaeltec, Scotland, UK) was used to measure the pressure. A total of 38 sets of pressure and flow were recorded for each tube. All data were acquired using Labview (National Instruments, Austin, Texas, USA) with sampling rates of 500Hz. Data were analysed using in house programs written in Matlab (The Mathworks, Natick, MA, USA).

In order to investigate the effect of the mechanical properties of the wall of the tube on wave dissipation, we repeated the experiment but with modifying the properties of the wall of the 16mm diameter tube; a thread of strong cotton wound with a pitch of approximately 30^{o} around the circumference of the tube in the longitudinal direction.

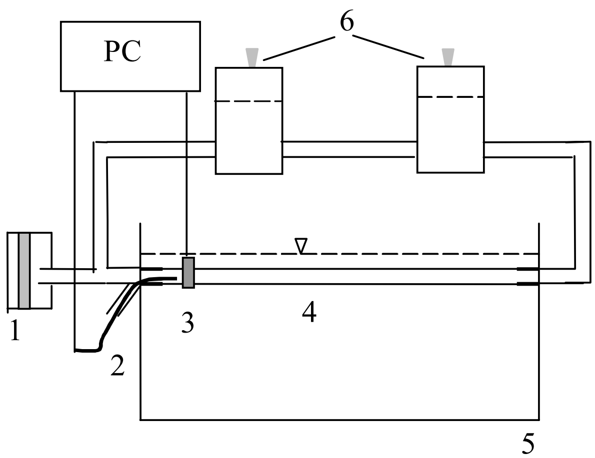
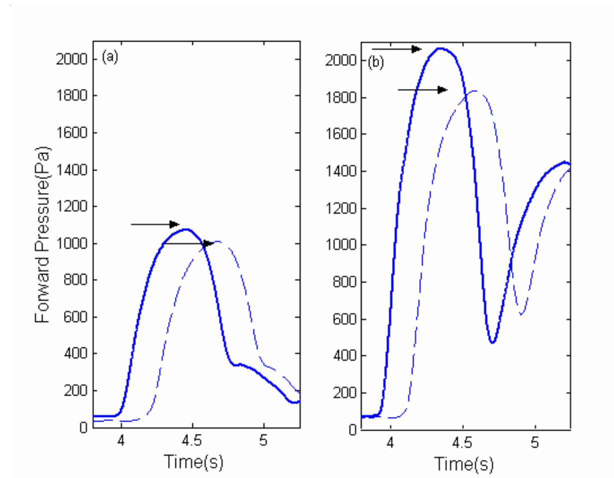


Fig.1. Setup of experiment. 1: Pump (Pulse generator); 2: Pressure transducer tipped catheters; 3: Flow probe; 4: Latex tubes of 200 cm in length; 5: Tank that contains water to a level just above the tube. 6: Water reservoirs.



(a) (b)

Fig.2 Forward pressure wave in 16mm normal tube (a) and modified tube (b). Solid line represents measurement of 20cm and dash line represents 45cm away from the inlet. Horizontal axis is time and vertical axis is forward pressure. The arrows indicate the magnitude of the forward pressure, while the difference between two arrows shows the dissipation of forward pressure between measurement of 20cm and 45cm.

B. Analysis

The measurement equipment of both flow and pressure were calibrated in advance before each experiment. With the flow meter, 1*Volt*= 2 *l/min* for 8mm flow probe. For the 16 mm flow probe, 1 *Volt*= 10 *l/min*. Velocity was obtained from measured flow and corresponding area of flow probe. The pressure was calibrated using water column method. The pressure was linear proportion to voltage and the relationship between pressure and voltage was, *P=19865Volt-556,* in Pascal.

The separated forward pressure wave, forward wave intensity were calculated using equations (5), (6) and (7). The separated forward pressure at the measurement of 20cm and 45cm away from inlet were shown in the Fig.2. The degree of wave dissipation within these two measurement sites was indicated by the difference of peak of forward pressure. The forward wave intensity had two peaks, which is shown in Fig3. The first one represents the forward compression wave and the second represents the forward expansion wave. Wave energy was calculated by integrating

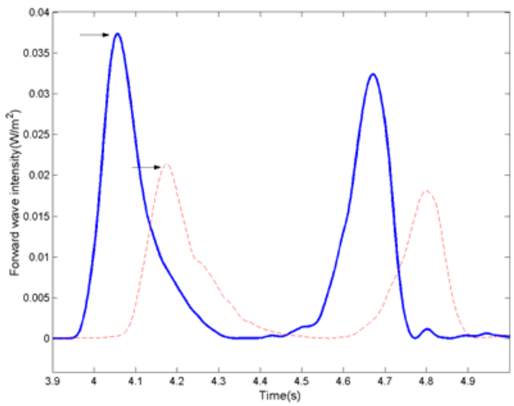


Fig.3. Forward wave intensity varied with time at measurement of 15cm and 40cm away from the inlet. Solid line represents measurement of 15cm and dash line represents 40cm. Arrows indicate the maximum of wave intensity at measurement of 15cm and 40cm, respectively.

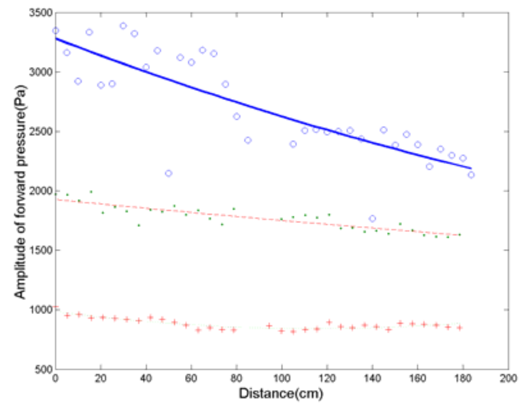


Fig.4. Amplitude of Forward pressure against distance travelled. Solid line (top) represents 8mm tube, dash line (middle) represents 16mm with modified wall and dot line (bottom) represents 16mm normal latex tube. Horizontal axis is distance and vertical axis is amplitude of forward pressure. Symbol: 'o' is data for 8mm tube, '·' for 16mm modified tube and '+' for 16mm normal tube.

the time history of wave intensity. The amplitude of forward pressure was obtained from the difference between first peak and static pressure and the values are presented in the Fig.4.

IV. RESULT

A. *Dissipation of the forward pressure*

Fig.2 shows the variation of the forward pressure with time at known sites of measurement, where (a) indicates waveform of forward pressure for 16mm normal tube and (b) for 16mm modified tube. The peak of the forward pressure decreased exponentially with distance, which can be seen in Fig.4. At the same sites of measurement, the amplitude of forward pressure is highest in 8mm diameter tube, the middle is 16mm modified tube and the lowest is 16mm normal tube.

B. *Dissipation of wave intensity*

The separated forward wave intensity are given in the Fig.3, where wave intensity varied with time and space is presented. The solid line is for 16mm normal tube at measurement of 15cm and dotted line is for 40cm. The arrows indicate the maximum of wave intensity at different sites, respectively, while the difference of two arrows indicates that the wave intensity dissipated when the wave was running from site of 15cm to 40cm. Fig.5 shows dissipation of the maximum of wave intensity with the travelled distance. Style of lines was used to specify the regression for experiments results in different sizes and properties of tube. The leading curve is for 8mm diameter tube; the lowest is for 16mm diameter normal tube and the middle one for 16mm diameter modified tube.

C. *Dissipation of the wave energy*

Fig.3 also shows the dissipation of wave energy. The area under the two peaks (compression wave and expansion wave) signifies the wave energy, while variation between the area under the solid peaks and dotted peaks implies wave energy dissipation during this phase. The dissipation of the wave energy against the distance is also shown in the Fig.6. One can see that the wave energy decreased exponentially along the distance travelled. Likewise, styles of lines were specified for three experiment results, respectively.

V. DISCUSSION

The experimental results show that the forward pressure decreased along the distance. In the 16mm normal tube forward pressure decreased approximately 100Pa between 20cm and 45cm away from the inlet, which is shown in the Fig.2. (a). This event can also be seen in Fig.4, where the amplitude of forward pressure is noticeably decreased with the distance under the three conditions. In addition, the effect of the size of the tubes and mechanical properties on the degree of dissipation of the forward pressure wave can be found in this Fig. One can see that within 200cm the magnitude of forward pressure decreased approximately 40% in 8mm diameter tube and 20% in the 16mm diameter normal and modified tubes. It is clear that small sized tubes result in greater dissipation than large tubes do. For the same sized tubes, different mechanical properties have no discernable effect on wave dissipation.

The results in this study about the effect of size of tube on wave dissipation disagree with the previous findings by Anliker [4], in which the wave dissipation was not sensitive to the thickness ratio (wall thickness/tube radius)of tube. In our experiment, the wall thickness for both 8mm tube and 16mm tube were approximately 2mm. It is evident in our study that thickness ratio had an effect on wave dissipation. We believe that this difference in results might be attributed to the fact that the length of tube in our study was longer than that in other investigators' experiments.

Likewise, both wave intensity and wave energy dissipated exponentially with the distance, as seen in Fig.5 and Fig.6. More details about the dissipation of wave intensity and wave energy can be seen in the Fig.3. Maximum of wave intensity decreased approximately 40% between

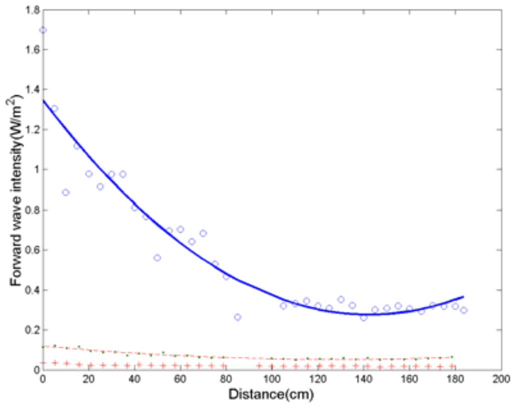


Fig.5. Maximum of wave intensity against distance travelled. Solid line (top) is for 8mm tube, dash line (middle) for 16mm modified tube and dot line (bottom) for 16mm normal tube. Horizontal axis is distance. Vertical axis is maximum value of wave intensity. Symbol: ‘o’ is data for 8mm tube, ‘·’ for 16mm modified tube and ‘+’ for 16mm normal tube.

measurement sites of 15cm and 40cm. The area under two peaks of the solid line is clearly larger than that under the dash line.

Furthermore, the effect of both size of tube and mechanical property on wave intensity and wave energy dissipation are also shown Fig5 and Fig6. It can be seen in 8mm tube that dissipation of maximum of wave intensity and wave energy was approximately 75% within 200cm of distance; while in 16mm tube it was approximately 50%. It is evident that the size of tube has a strong effect on wave intensity and wave energy dissipation. In addition, the effect of mechanical properties on wave dissipation is also shown in those diagrams. The dissipation of wave intensity and wave energy in 16mm modified tube was roughly equal to those in normal tube. This result gives further evidence that size of tube has a discernable effect on wave dissipation but the effect of mechanical property is not significant.

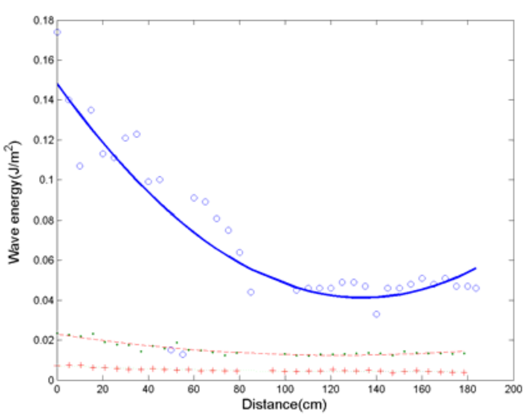


Fig.6. Forward wave energy against distance travelled. Solid line (top) represents 8mm tube, dash line (middle) for 16mm modified tube and dot line (bottom) for 16mm normal tube. Horizontal axis is distance. Vertical axis is wave energy. Symbol: ‘o’ is data for 8mm tube, ‘·’ for 16mm modified tube and ‘+’ for 16mm normal tube.

VI. Conclusion

We conclude that the magnitude of the separated forward pressure, wave intensity and wave energy dissipated exponentially with the distance. The size of the tube has a significant effect on wave dissipation and the smaller the size of the tube, the greater the dissipation. The effect of the mechanical properties of the wall of the tube on wave dissipation is not discernable.

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