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PRESSURE WAVES INDUCED BY TRANSIENTS IN A PIPE FLOWING FLUID

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ABSTRACT

This paper presents some simulation results of fluid transients in a common tubular circuit (a cavity connected to a pipeline) used to validate the code TRANS. The transients are simulated considering the classical plane wave theory. Partial differential equations ruling the problem are solved by the general characteristics' technique using the method of finite differences. A special attention is given to cavitation process, which is taken into account through an heuristic 1-D model. The wave speed of the mixture is adjusted dynamically. Tue validation case includes some important hydraulic phenomena: membrane rupture, sudden valve closure and several singularities.

Keywords: Transients, cavitation, pipeline, plane-waves.

1. INTRODUCTION

On the literature the classical study of transients considering 1D-propagation of flat waves proved to be accurate enough to simulate several kinds of problems in pipelines (Pedroso et al., 1992 to 1994), such as sudden valve closure, depressurization, rupture of safety membranes and any sort of pressure oscillations. Not only in nuclear power plants but mainly in the petrol industry hydraulic phenomena must be considered as cause or consequence of many possible accidents. However in a lot of industrial applications the transport of high pressure fluid through pipelines can be affected by cavitation. This generates two-phase flows much more difficult to be evaluated by simple commercial codes.

Simplified 1-D formulations make use of several kinds of experimental factors to take into account material properties of the fluid and effects originated on the 3-D geometry of the real problem. Cavitation is a typical 3-D effect caused by formation and collapse of gas bubbles. To simulate this behavior in a simple model it is necessary to make an heuristic approach to the phenomenon.

The main idea is to analyze experimental results and try to capture the main effects of the presence of bubbles on the propagation of transient: pressure is limited to the vapor pressure, sound velocity is reduced, dissipation experiences an increase and collapse of bubbles generates impulses to be added to the transient. There are different ways to deal with this problem. Streeter(1971) focused on the physics of the Bubble but here we use the more heuristic approach of Hurwitz(1981). We propose an additional correction on the sound velocity.

In the validation study case some important hydraulic phenomena are considered together: a membrane rupture and a sudden automatic valve closing generates a water hammer, that is attenuated by singularities on the pipeline, but mainly by cavitation. The experimental data are very important to adjust several important calibration parameters on the validation of the code.

2. GENERAL FORMULATION FOR THE CASE TRANSIENTS IN FLUIDS

The classic water-hammer theory is adopted for modeling the fluid behavior. Theoretical-numerical approaches of pressure wave propagation have been the object of several of our studies (Pedroso,'et al', 1992 to 1994). The equations ruling this problem are the equations of continuity, quantity of movement and state, respectively

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{1}$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + f\,\frac{v|v|}{2D} = 0 \tag{2}$$

$$f(p,\rho) = Cte \quad \Leftrightarrow \quad \tilde{p} = \tilde{\rho}\, c^2 \ (linearized) \ \therefore \ c^2 = \frac{K^*}{\rho}\,. \tag{3}$$

Where c is the sound velocity in fluid; K^* is the fluid volumetric modulus of elasticity, p is the pressure, v is the velocity, ρ is the specific mass of the fluid.

Applying the linearized state equation (3) on the continuity equation (1) we have

$$\frac{\partial p}{\partial t} + v\frac{\partial p}{\partial x} + \rho\, c^2 \frac{\partial v}{\partial x} = 0 \tag{4}$$

Supposing an adequate ratio between mesh spacing time step is chosen, the following characteristic equations are obtained:

$$\frac{dv}{dt} \pm \frac{1}{\rho c}\frac{dp}{dt} + \frac{fv\,|\,v\,|}{2D} = 0 \qquad \therefore \ \frac{dx}{dt} = V \pm c \tag{5}$$

The ±c values represent the inclination of the characteristic curve in x-t plane; f is the coefficient of friction, D is the diameter of the pipe;

3. CAVITATION MODEL

The model presented above doesn't make any assumptions about negative values for pressures. In a real flow the pressure of the fluid is limited to vapor pressure. The first simple assumption we do here is to keep pressure equal to the vapor pressure in a particular node every time it reaches this level. The second assumption is to start a routine to calculate the growth and collapse of the bubble:

$$V_B = \sum_t (v_u - v_d) A\, dt \tag{6}$$

Where V_B is the bubble size, v_u the upstream velocity at the cavitating node, v_d the downstream velocity at the cavitating node and A is the pipe cross sectional area.

We suggest then a recalculation of the sound velocity at the pipe considering the total volume of bubbles. According to Pedroso(1994):

$$\frac{1}{c^2} = \frac{1-\tilde{\alpha}}{c_f^2}\left(1 - \tilde{\alpha} + \tilde{\alpha}\frac{\rho_g}{\rho_f}\right) + \frac{\tilde{\alpha}}{c_g^2}\left[\tilde{\alpha} + (1-\tilde{\alpha})\frac{\rho_f}{\rho_g}\right] \tag{7}$$

where the relative gas volume is given by:

$$\tilde{\alpha} = \frac{\sum_L V_B}{V_P + \sum_L V_B}$$

$\sum_L V_B$ is the total volume of bubbles ins pipe of length L, V_P is the volume of the pipe, ρ_g is the specific mass of the gas (1.2 Kg/m^3), ρ_f is the specific mass of the fluid (1000 Kg/m^3), c_g is the sound velocity on the gas (393 m/s) and c_l the sound velocity on the fluid (1481 m/s). Figure 1 shows the influence of the relative amount of gas on the sound velocity of the mixture. It is very sensitive to small amounts of gas.

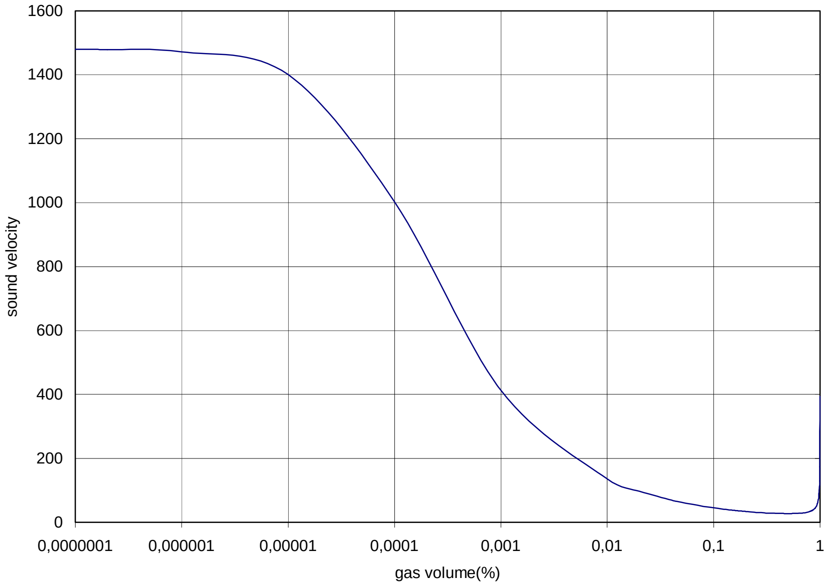

Figure 1 – Influence of gas volume on sound velocity.

The last assumption in the cavitation model is the generation of an acoustic overpressure pulse each times a bubble collapses, that happens when V_B becomes zero. Its amplitude it calculated with

$$\Delta p = \rho c(v_u - v_d)\ . \qquad (8)$$

To validate this model we present now a comparison with an experimental result.

4. RESULTS

The experimental results to be presented were taken on system “CLAUDIA” (Figure 2) (Huet & Garcia, 1985) conceived at CEA - Cadarache – France. It is basically a pipeline (length ≈ 22m, diameter=0.146m) connected to a cavity at one end ,that keeps a constant high pressure (≈30 Bars), and at the other end there is a membrane and a valve adjusted to close automatically (closing time = 68 ms) after rupture of the membrane. The transient generated by rupture of membrane will create a suppression wave, that will generate cavitation bubbles on the system.

Figure 3 shows the closing angle of the valve, from 56°(opened) to 90°(closed) and the equivalent factor used at the simulation to represent the whole process of rupture of the membrane e consequent closing of the valve, from TAU=0(closed) to TAU=1 (opened).

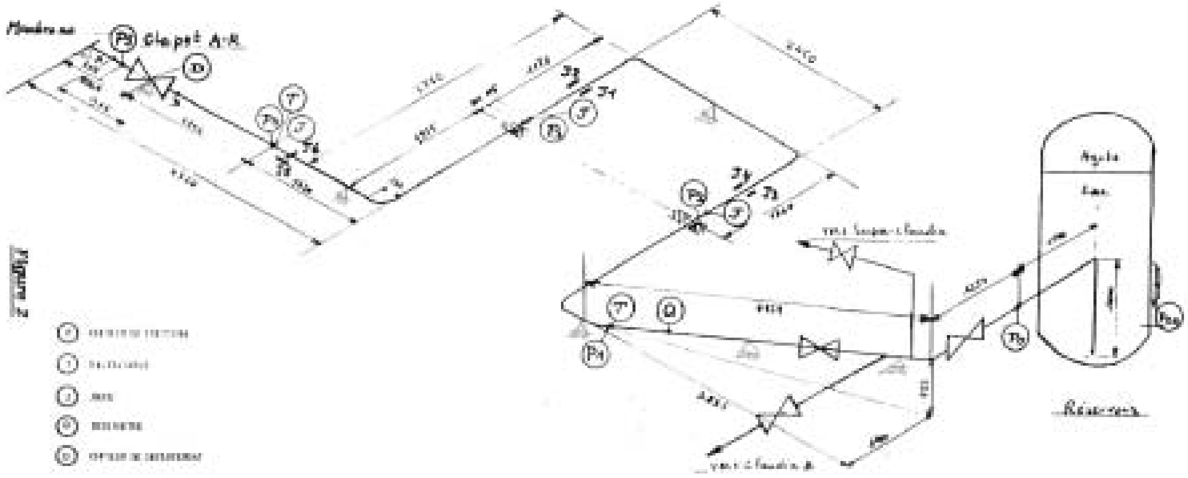

Figure 3 in the source is stacked directly beneath this caption:

Figure 2 – CLAUDIA system (Huet & Garcia, 1985).

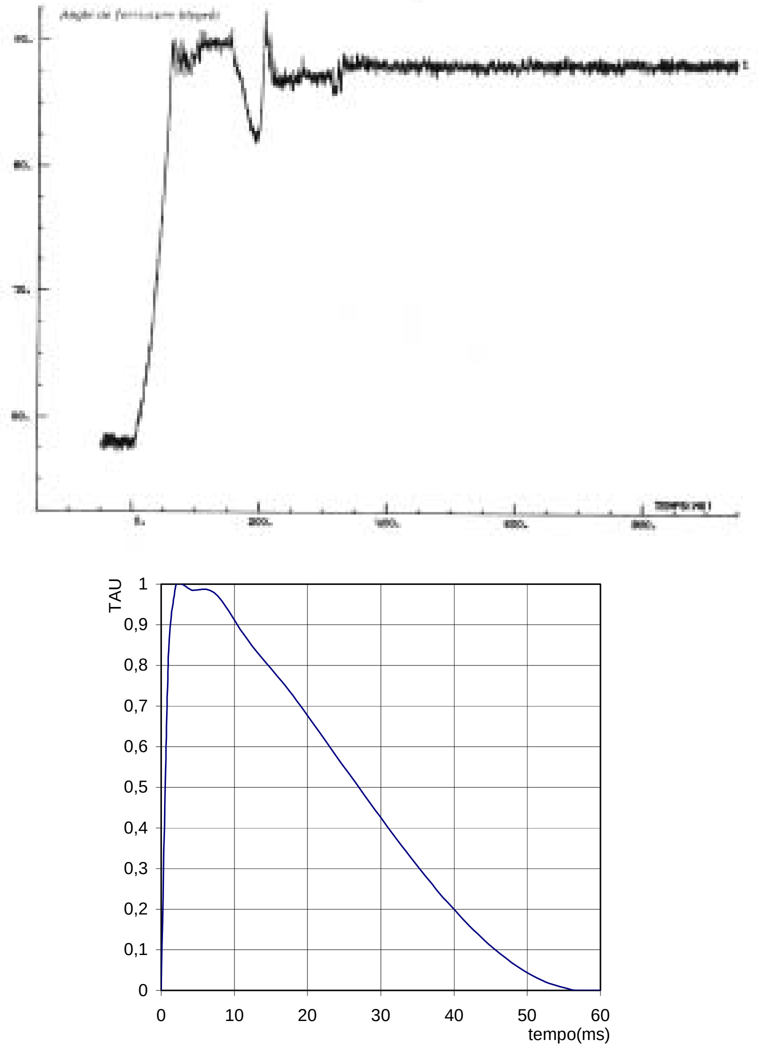

Figure 3 – Valve closing curves, experimental and numerical.

Equations (2) and (4) define a first-order quasi-linear hyperbolic system of partial differential equations with p an v as dependent variables. When this system is transformed into ordinary differential equations (5) by the method of characteristics, two families of propagating characteristic lines are found. To derive the finite difference equations each compatibility equation is integrated along its apropriate characteristic line represented on the computational space-time grid.

To reproduce the experimental results there are many factors to be calibrated on the model. At first the valve closing curve must represent the complex behavior of the rupture of membrane and subsequent valve closing. In the starting process of sudden depressurization the coefficient of friction must be adjusted so that the outflow corresponds the experimental values. The most sensitive factor on this process is the dynamic calculation of the volume of the bubbles. As we see on the curve on figure 1 sound velocity of mixture is very sensitive to small amounts of gas. It can be necessary to adjust equation (6) to a specific problem.

Figure 4 shows the experimental results and also the simulation. Pressures were measured at captor P4, (Fig. 2), and Figure 5 the corresponding outflow at point Q (Fig. 2).

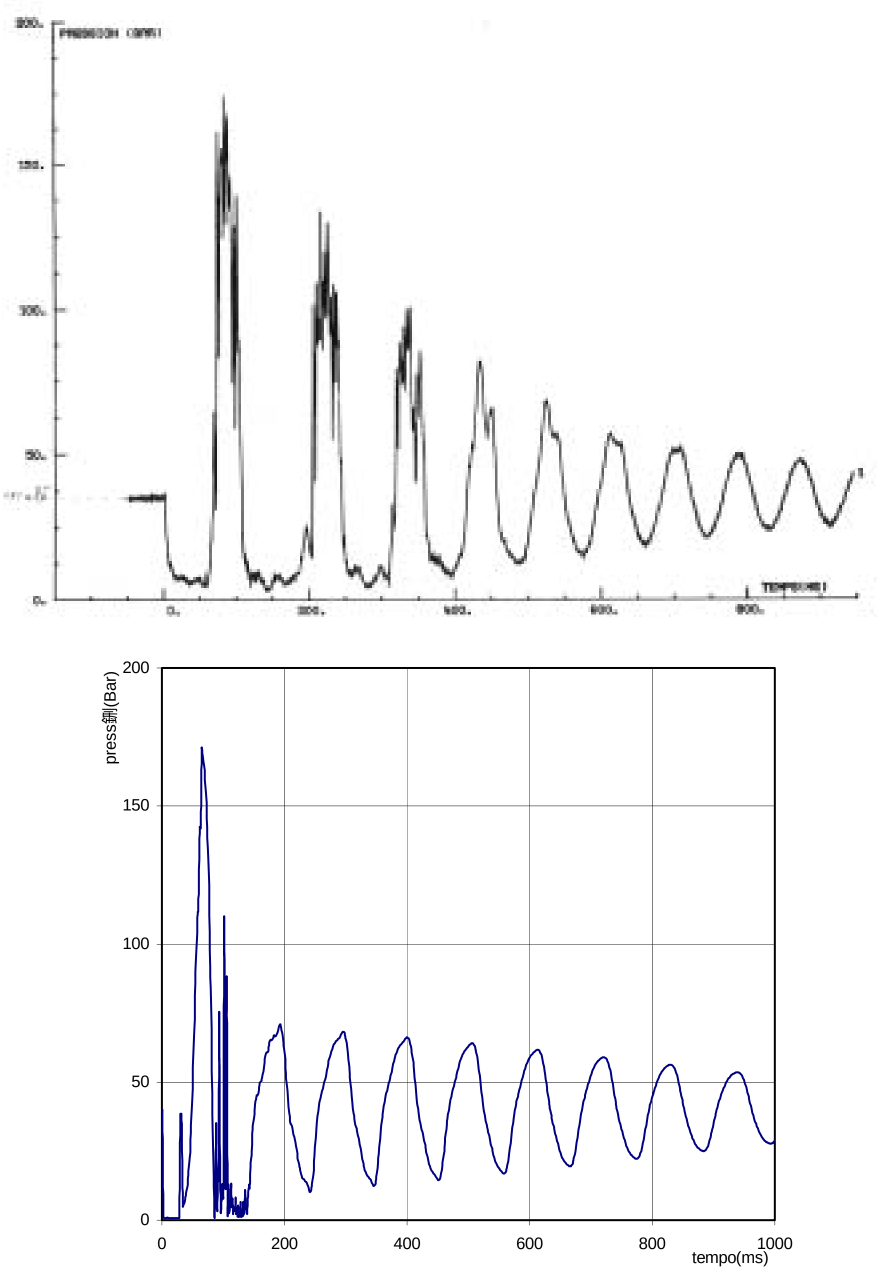

Figure 4 – Pressure at P4 – experimental and numerical results.

In the comparison of the curves presented in figures 5 and 6 we can notice that:

- The amplitudes of the first peaks for both pressure and outflow presents a very good agreement to the experimental values.
- The dynamic adjustment of sound velocity of mixture proved to work well for this case. The start value was 1481m/s and the combined adjusted value is approximately 835m/s.
- The secondary effect caused by collapse of cavitation bubbles is observed on the simulation also, but the recovery of pressure after the first suppression wave wasn't well represented by the model.

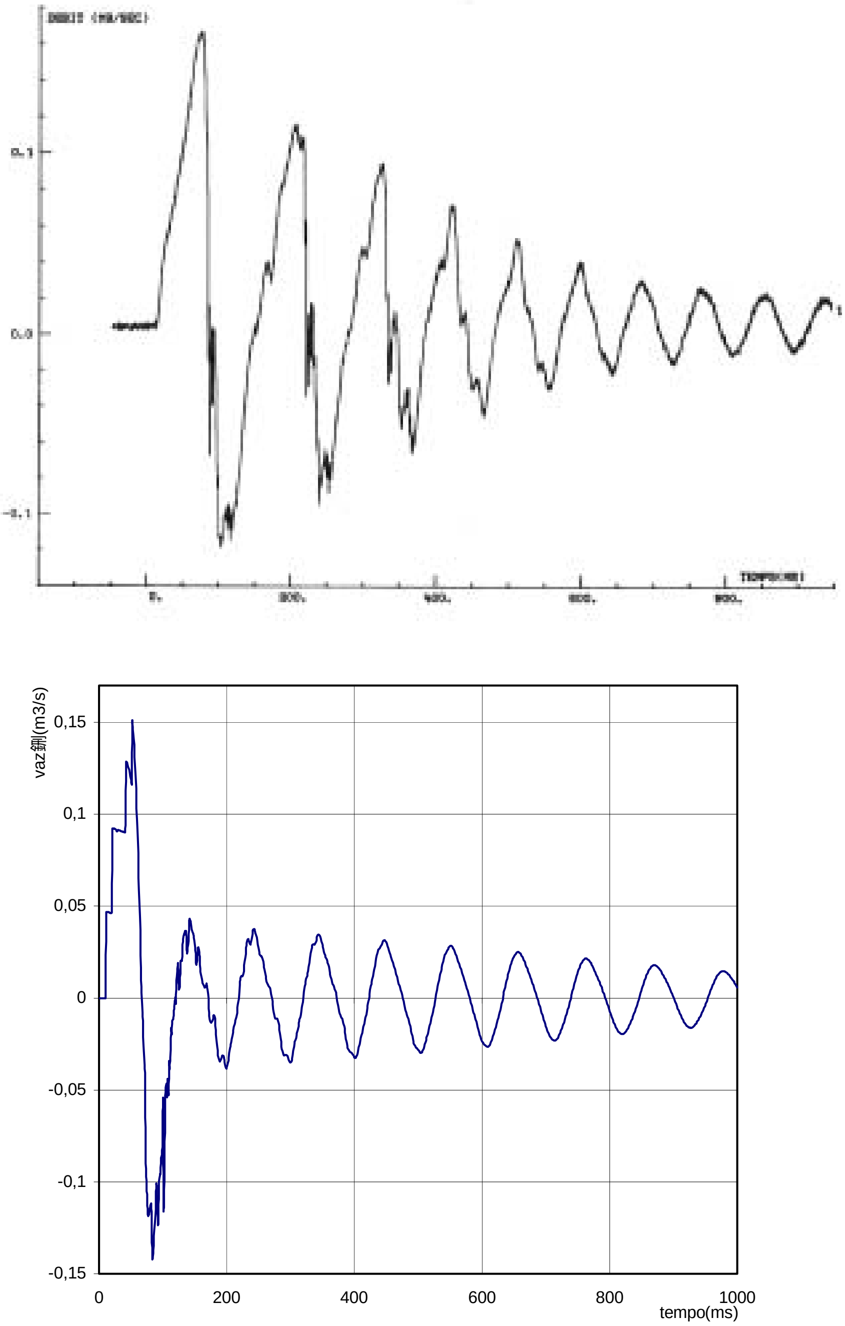

Figure 5 – Outflow at Q, experimental and numerical results.

5 CONCLUSIONS

Within the possible applications of a simple model for calculation of transients in a pipeline, the heuristic model presented in this paper to take into account effects of cavitation achieved very good agreement to experiments. The first amplitudes and the dynamic adjustment of sound velocities are very important characteristics of the dynamic response of the system. However, it is possible to use the flexibility of an heuristic approach to make further improvements on this transient simulation.

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