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AN ANALYSIS OF THE METHOD OF STREETER AND WYLIE FOR MULTIDIMENSIONAL WAVE PROPAGATION

MASTER

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ABSTRACT

The method of Streeter and Wylie was developed to allow calculation of two- and three-dimensional transients using existing one-dimensional "water-hammer" codes for waves in fluid piping networks. The method is analyzed in terms of the effective multidimensional finite-difference scheme it generates. Subject to certain modelling restrictions, the method produces a first-order accurate scheme in the linear-acoustic, constant-properties approximation. Despite the fact that conventional multidimensional techniques are far more efficient, the method continues to be used in the engineering community.

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AN ANALYSIS OF THE METHOD OF STREETER AND WYLIE FOR MULTIDIMENSIONAL WAVE PROPAGATION

Introduction

Fluid dynamic and wave propagation problems in two or three dimensions are sometimes calculated using the method of Streeter and Wylie.¹ In this method, the fluid sheet or volume is represented by a network or lattice of fluid-filled pipes having finite flow-area, but assumed to intersect at ideal points. The one-dimensional equations are then solved for each pipe (or "leg"), subject to continuity of pressure and to conservation of mass at each junction (or "node").

Many workers with a background in conventional multidimensional codes are initially skeptical of this procedure. However, if an appropriate "scaled" sonic velocity is used in the pipe equation,² it may be demonstrated to yield acceptable agreement with other methods in many cases. This suggests that the method does in some sense define an approximate multidimensional algorithm.

We will demonstrate explicitly that the Streeter-Wylie method, with a first-order-accurate one-dimensional algorithm for the legs, provides a first-order accurate algorithm for the two-dimensional fluid equations in the linear acoustic limit where the particle velocity u is much less than the sonic velocity c , and where material properties are time-independent. The requirements are that the sonic velocity be scaled, and that the flow area per width in the network be independent of direction. We will discuss briefly the validity of various generalizations and extensions of this simple case.

Analysis

Consider the Streeter-Wylie pipe grid as just another way to generate a finite-difference representation of a set of partial differential equations -- hopefully, of the wave equation. Pressures are naturally defined at pipe

junctions; let these be the nodes for the finite-difference mesh. In two dimensions,³ four pipes meet at each node, and a particle velocity is defined for each. Let the velocities in pipes parallel the x axis be denoted by $\dot{u}$ and u , and those in pipes parallel the y axis by $\dot{v}$ and v , with the position of the dot denoting the position of the junction relative to the pipe end. The finite-difference mesh is shown in Figure 1, x and y coordinates are denoted by subscript i and j, and time levels by superscript n, e.g., P_{ij}^n .

Four waves arrive at junction (i,j) at time t^{n+1} . The one from the left is, by the method of characteristics,

$$\left[P + (\rho c)_{i-1/2j} \dot{u} \right]_{ij}^{n+1} = \left[P + (\rho c)_{i-1/2j} \dot{u} \right]_{i-(c\Delta t/\Delta x)_{i-1/2j}^{n+1/2}}^n \quad (1)$$

in the linear acoustic approximation. Here P, ρ , and c are the fluid pressure, mass density, and sonic velocity, respectively, and $\Delta t^{n+1/2} = t^{n+1} - t^n$ is the time step. The velocity on the right-hand side lacks a dot, as it is not at a pipe end. The entire right-hand side must be determined by interpolation. The point must lie between (i-1,j) and (i,j) for stability and, if linear interpolation between these points is used, the result is

$$\begin{aligned} P_{ij}^{n+1} + (\rho c)_{i-1/2j} \dot{u}_{ij}^{n+1} &= P_{ij}^n + (\rho c)_{i-1/2j} \dot{u}_{ij}^n \\ &+ \left(\frac{c\Delta t}{\Delta x} \right)_{i-1/2j}^{n+1/2} \left[P_{i-1j}^n - P_{ij}^n + (\rho c)_{i-1/2j} \left(\dot{u}_{i-1j}^n - \dot{u}_{ij}^n \right) \right] \quad (2) \end{aligned}$$

Similarly, the left-moving wave is

$$\begin{aligned} P_{ij}^{n+1} - (\rho c)_{i+1/2j} \dot{u}_{ij}^{n+1} &= P_{ij}^n - (\rho c)_{i+1/2j} \dot{u}_{ij}^n \\ &+ \left(\frac{c\Delta t}{\Delta x} \right)_{i+1/2j}^{n+1/2} \left[P_{i+1j}^n - P_{ij}^n - (\rho c)_{i+1/2j} \left(\dot{u}_{i+1j}^n - \dot{u}_{ij}^n \right) \right] \quad (3) \end{aligned}$$

Figure 1. Notation for Variables in Streeter-Wylie Pipe Grid

and there are analogous equations for the two waves parallel y.

Subtraction of Eq. 3 for node (i,j) from Eq. 2 for node (i + 1,j) yields

$$(\rho c)_{i+1/2j} \left(u_{i+1/2j}^{n+1} - u_{i+1/2j}^n \right) - 1/2 \left(P_{i+1j}^{n+1} - P_{ij}^{n+1} \right) - \left[1/2 - \left(\frac{c \Delta t}{\Delta x} \right)_{i+1/2j}^{n+1/2} \right] \left(P_{i+1j}^n - P_{ij}^n \right) = 0, \quad (4)$$

where

$$u_{i+1/2j} \equiv 1/2 (u_{ij} + u_{i+1j}) \quad (5)$$

is the average velocity in the pipe connecting (i,j) to (i + 1,j).

Following the normal procedure of expanding terms in Eq. 4 in Taylor series about $\left(\begin{matrix} n+1/2 \\ i+1/2j \end{matrix} \right)$, one finds

$$\rho \frac{\partial u}{\partial t} + \frac{\partial P}{\partial x} = 1/2 \left(\Delta t - \frac{\Delta x}{\phi} \right) \frac{\partial^2 P}{\partial x \partial t} + O(\Delta^2), \quad (6)$$

where ρ , ϕ denote density and sonic velocity, respectively, in legs parallel x. Similarly,

$$\rho \frac{\partial v}{\partial t} + \frac{\partial P}{\partial y} = 1/2 \left(\Delta t - \frac{\Delta y}{\phi} \right) \frac{\partial^2 P}{\partial y \partial t} + O(\Delta^2), \quad (7)$$

where ρ , ϕ are for legs parallel y.

The equation for $\partial P / \partial t$ follows from conservation of mass, expressed by

$$\begin{aligned}
& (\rho A)_{i-1/2j} u_{ij} - (\rho A)_{i+1/2j} u_{ij} + (\rho A)_{ij-1/2} \dot{v}_{ij} \\
& - (\rho A)_{ij+1/2} \dot{v}_{ij} = 0 \quad .
\end{aligned} \tag{8}$$

First, however, we must address the fact that our model contains a non-physical variable. For each node, there are a pressure and three independent "velocities" (the fourth velocity is determined by Eq. 8) to represent the pressure and two components of velocity. We have chosen the combination of Eq. 5 to represent the physical x component of velocity, but must also consider the combination

$$\tilde{u}_{i+1/2j} \equiv u_{i+1j} - u_{ij} \quad . \tag{9}$$

The combinations $v_{ij+1/2}$ and $\tilde{v}_{ij+1/2}$ are similarly defined. Note that $\tilde{u}$ and $\tilde{v}$ are not independent -- Eq. 8 may always be used to eliminate one or the other.

Addition of Eq. 3 for node (i,j) to Eq. 2 for node (i+1,j), subtracting the result for n-1 from that for n, and expansion in Taylor series as before lead to

$$\frac{\partial \tilde{u}}{\partial t} = - \frac{\Delta x}{2} \frac{\partial^2 P}{\partial t^2} + O(\Delta^2) \quad . \tag{10}$$

Similarly

$$\frac{\partial \tilde{v}}{\partial t} = - \frac{\Delta y}{2} \frac{\partial^2 P}{\partial t^2} + O(\Delta^2) \quad , \tag{11}$$

which demonstrates clearly that $\tilde{u}$ and $\tilde{v}$ are not independent.

Now form the combination $(\Delta x/c^2)_{i-1/2j}$ (Eq. 2) + $(\Delta x/c^2)_{i+1/2j}$ (Eq. 3) + (two terms for waves parallel y) - $2\Delta t^{n+1/2}$ (Eq. 8).

The result is

$$\begin{aligned}
& \left[\left(\frac{A \Delta x}{c^2} \right)_{i-1/2j} + \left(\frac{A \Delta x}{c^2} \right)_{i+1/2j} + \left(\frac{A \Delta y}{c^2} \right)_{ij-1/2} + \left(\frac{A \Delta y}{c^2} \right)_{ij+1/2} \right] (P_{ij}^{n+1} - P_{ij}^n) \\
& = -2\Delta t^{n+1/2} \left\{ \left[\left(\rho u A \right)_{i+1/2j}^n - 1/2 \left(\frac{A}{c} \right)_{i+1/2j} (P_{i+1j}^n - P_{ij}^n) \right] \right. \\
& \quad \left. - \left[\left(\rho u A \right)_{i-1/2j}^n - 1/2 \left(\frac{A}{c} \right)_{i-1/2j} (P_{ij}^n - P_{i-1j}^n) \right] + \dots \right\} \\
& \quad + \left(\frac{\rho u A \Delta x}{c} \right)_{i+1/2j}^{n+1} - \left(\frac{\rho u A \Delta x}{c} \right)_{i+1/2j}^n \\
& \quad - \left(\frac{\rho u A \Delta x}{c} \right)_{i-1/2j}^{n+1} + \left(\frac{\rho u A \Delta x}{c} \right)_{i-1/2j}^n + \dots \\
& \quad - \left(\frac{\rho \tilde{u} A \Delta x}{2c} \right)_{i+1/2j}^{n+1} + \left(\frac{\rho \tilde{u} A \Delta x}{2c} \right)_{i-1/2j}^n \\
& \quad - \left(\frac{\rho \tilde{u} A \Delta x}{2c} \right)_{i-1/2j}^{n-1} + \left(\frac{\rho \tilde{u} A \Delta x}{2c} \right)_{i-1/2j}^n + \dots \quad (12)
\end{aligned}$$

The Taylor series expansion about $( )_{ij}^{n+1/2}$ yields

$$\begin{aligned}
& \left(\frac{A}{\Delta y \epsilon^2} + \frac{A}{\Delta x \epsilon^2} \right) \frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left(\rho u A / \Delta y \right) + \frac{\partial}{\partial y} \left(\rho v A / \Delta x \right) \\
& = 1/2 \frac{\partial}{\partial x} \left\{ \frac{A}{\Delta y} \left[\left(\Delta t + \frac{\Delta x}{\epsilon} \right) \rho \frac{\partial u}{\partial t} + \frac{\Delta x}{\epsilon} \frac{\partial P}{\partial x} \right] \right\} - 1/2 \frac{A}{\Delta y \epsilon} \rho \frac{\partial \tilde{u}}{\partial t} \\
& \quad + 1/2 \frac{\partial}{\partial y} \left\{ \frac{A}{\Delta x} \left[\left(\Delta t + \frac{\Delta y}{\epsilon} \right) \rho \frac{\partial v}{\partial t} + \frac{\Delta y}{\epsilon} \frac{\partial P}{\partial y} \right] \right\} - 1/2 \frac{A}{\Delta x \epsilon} \rho \frac{\partial \tilde{v}}{\partial t} + O(\Delta^2) \quad (13)
\end{aligned}$$

Note that A , $\tilde{u}$, $\partial \tilde{u} / \partial t$ and $\partial \tilde{v} / \partial t$ are $O(\Delta)$.

We could now proceed, in the conventional way, to replace time derivatives on the right-hand sides (error terms) of Eqs. 6, 7, and 13 by spatial derivatives, using Eqs. 6, 7, 10, 11, and 13. We note first, however, that the lowest order terms imply

$$\left(\frac{A}{\Delta y e^2} + \frac{A}{\Delta x \phi^2} \right) \frac{\partial^2 P}{\partial t^2} - \frac{\partial}{\partial x} \left(\frac{A}{\Delta y} \frac{\partial P}{\partial x} \right) - \frac{\partial}{\partial y} \left(\frac{A}{\Delta x} \frac{\partial P}{\partial y} \right) = o(\Delta). \quad (14)$$

Therefore, the difference scheme represents the wave equation if, and only if,

$$A/\Delta y = A/\Delta x = h, \quad (15)$$

where h , which may be a function of x and y , is proportional to the thickness of the sheet. Under this restriction, the difference equations become

$$\begin{aligned} & \frac{h}{c^2} \frac{\partial^2 P}{\partial t^2} + \frac{\partial}{\partial x} (\rho u h) + \frac{\partial}{\partial y} (\rho v h) \\ &= -1/2 \left[\frac{c^2}{e^2} (\Delta t - \Delta x/e) + \frac{c^2}{\phi^2} (\Delta t - \Delta y/\phi) \right] \left[\frac{\partial}{\partial x} \left(h \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left(h \frac{\partial P}{\partial y} \right) \right] \\ &+ o(\Delta^2) \quad ; \end{aligned} \quad (16)$$

$$\rho \frac{\partial u}{\partial t} + \frac{\partial P}{\partial x} = 1/2 \left(\Delta t - \frac{\Delta x}{e} \right) \frac{\partial^2 P}{\partial x \partial t} + o(\Delta^2) \quad ; \quad (6)$$

$$\rho \frac{\partial v}{\partial t} + \frac{\partial P}{\partial y} = 1/2 \left(\Delta t - \frac{\Delta y}{\phi} \right) \frac{\partial^2 P}{\partial y \partial t} + o(\Delta^2) \quad ; \quad (7)$$

where

$$c^2 \equiv e^2 \phi^2 / (e^2 + \phi^2) \quad (17)$$

is the effective sonic velocity in the network. This is a generalization of Fabric's result²

$$\epsilon = \phi = \sqrt{2} \ c \quad (\text{Fabric}) \quad (18)$$

Equations 16, 6, and 7 are, to first order in Δx , Δy and Δt , the two-dimensional fluid equations in the linear-acoustic, constant-properties limit.

We note that, if the mass fluxes ρu and ρv are considered basic (rather than u and v), ρ and ϕ need not be equal. Also ϵ and ϕ need not be equal -- only the combination in Eq. 17 appears to lowest order. The only requirement is that Eq. 15 be satisfied, i.e., that flow area per width be equal in the x and y directions.

Examples

A few simple calculations were run with the WHAM code⁴ to illustrate results of the previous section. WHAM uses a special case of the method just described: $c\Delta t = n\Delta x$ for some integer n for each pipe. Therefore, a wave moves unaltered from one end to the other in n steps, without interpolation. (If $n > 1$, the intermediate points are stored.)

The first example is the propagation of a 400 psi one-dimensional relief wave through water initially at 2100 psia and 544°F, with reflection from a rigid boundary. The two networks of Figure 2, representing different ways a unit strip can be cut from a two-dimensional grid, give identical results which are shown in Figures 3 and 4. The exact⁵ positions of the wave front at each time are indicated by a short vertical line. The exact pressure and velocity behind the initial wave are 1700 psia and 11.7 ft/second, respectively, while those behind the (doubled) reflected wave are 1300 psia and 23.4 ft/second. The WHAM results may be seen to be entirely typical of an undamped, first-order-accurate wave-code.

The second example is the radial propagation of a relief wave in two dimensions. The boundary condition is imposed by controlling the pressure of a single node, corresponding to a boundary pressure at some imperfectly defined radius less than x . The calculation may be viewed, in a sense, as a numerical

Figure 2. Networks for First Example. All pipes are unit area except horizontal pipes in b, which are half-unit. All pipe lengths are Δx or $\frac{1}{2}\Delta x$.

Figure 3. Pressure Profiles for First Example

Figure 4. Velocity Profiles for First Example

Green's function. Initial conditions and boundary pressures are as in the preceding case. The three cases shown in Figures 5 and 6 are:

$$(1) \Delta x = \Delta y = .594 \text{ ft}, A = A, e = \phi = \sqrt{2} \text{ c}, t = 1.25 \text{ ms} = 7.07\Delta y/c$$

$$(2) 2\Delta x = \Delta y = .594 \text{ ft}, A = 2A, e = \phi = \sqrt{2} \text{ c}, t = 1.25 \text{ ms} = 7.07\Delta y/c$$

$$(3) 2\Delta x = \Delta y = .469 \text{ ft}, A = 2A, 2e = \phi = \sqrt{5} \text{ c}, t = 1.00 \text{ ms} = 7.16\Delta y/c$$

Note that the third case is plotted at a different time and with a different distant scale, so that the reduced time, $ct/\Delta y$, and reduced radius, $cr/\Delta y$, correspond to the first two cases. The symmetry in each case, and the agreement among the three cases, is quite acceptable for a first-order accurate numerical scheme.

Comments

Many applications of the Streeter-Wylie method employ generalizations and "improvements" of the simple scheme just described. We wish to emphasize that we have not demonstrated the validity of the generalizations or the value of the improvements. Specifically:

1. The full fluid equations may be used for the legs rather than the constant-properties, linear-acoustic approximation. While addition of the energy equation and of convective terms appears straightforward, the resulting multidimensional scheme may contain errors of order u/c , and we believe that it probably does.
2. Each leg may be subdivided into several cells for the one-dimensional computation. This does not increase the accuracy of the multidimensional scheme. The value of this approach as in interpolation scheme is unclear.

Figure 5. Pressure Profiles for Second Example

$\Delta x = \Delta y$
 $e = \phi$

Figure 6. Velocity Profiles for Second Example

3. The first-order accurate one-dimensional scheme described may be replaced by one of higher order (this requires subdivision of the legs). We believe that the resulting multidimensional scheme will be only first-order accurate. This will certainly be the case if the scheme is one for which boundary conditions are only first-order.

Also, it is well known that a finite difference code cannot resolve details finer than about $2\Delta x$ -- this is the shortest wavelength which can be represented. Therefore, a Streeter-Wylie calculation cannot be expected to have resolution better than about 2 leg-lengths. Each leg may be subdivided to provide greater detail but, from the point of view of this analysis, the detail is spurious.

Finally, we wish to note that a conventional multidimensional code, run with the same resolution (Δx and Δy), requires less computer time and less core storage⁶ than a Streeter-Wylie calculation. The principal reason is that, for the pipe grid (in two dimensions), each computational mesh or junction corresponds to four pipe ends, and requires four sets of stored variables and four solutions of the difference equations as well as solution of the junction equations. Moreover, the pipe network is extremely awkward. Its artificial nature invites errors both in setup and in interpretation. The problem of extracting values at (x,y) from a table indexed by pipe number is particularly vexing.

Notes and References

1. V. L. Streeter and E. B. Wylie, "Two and Three-Dimensional Fluid Transients," Trans. ASME, 90, 501(1968).
2. S. Fabric, "Two- and Three-Dimensional Fluid Transients," Trans. ANS 14, 360(1971).
3. The extension to three dimensions is straightforward, requiring only the addition of terms for waves parallel z.
4. S. Fabric, Computer Program WHAM for Calculation of Pressure, Velocity and Force Transients in Liquid Filled Piping Networks, Report No. 67-49-R, Kaiser Engineers, November 1967.
5. Here "exact" means the linear-acoustic, constant properties result, which is extremely accurate since $u/c < .007$, and the acoustic impedance, ρc , varies by less than 2% over the exact relief isentrope.
6. Specifically, compare CSQ (Samuel L. Thompson, CSQ-A Two Dimensional Hydrodynamic Program with Energy Flow and Material Strength, SAND74-0122, Sandia Laboratories, Albuquerque, New Mexico, August 1975) with WHAM/MOD-007, including improvements by E. D. Throm (Memo to Z. R. Rosztoczy, Chief, Analysis Branch DSS, USNRC, dated July 7, 1976), both run on a CDC 6600. With a simple equation of state, CSQ runs at 5×10^6 mesh-cycles/hour and stores 9 variables per cell. WHAM, which has no equation of state, runs at about 1×10^6 mesh-cycles/hour, and stores at least 98 variables per node (4-junction) when used with a rectangular network.

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