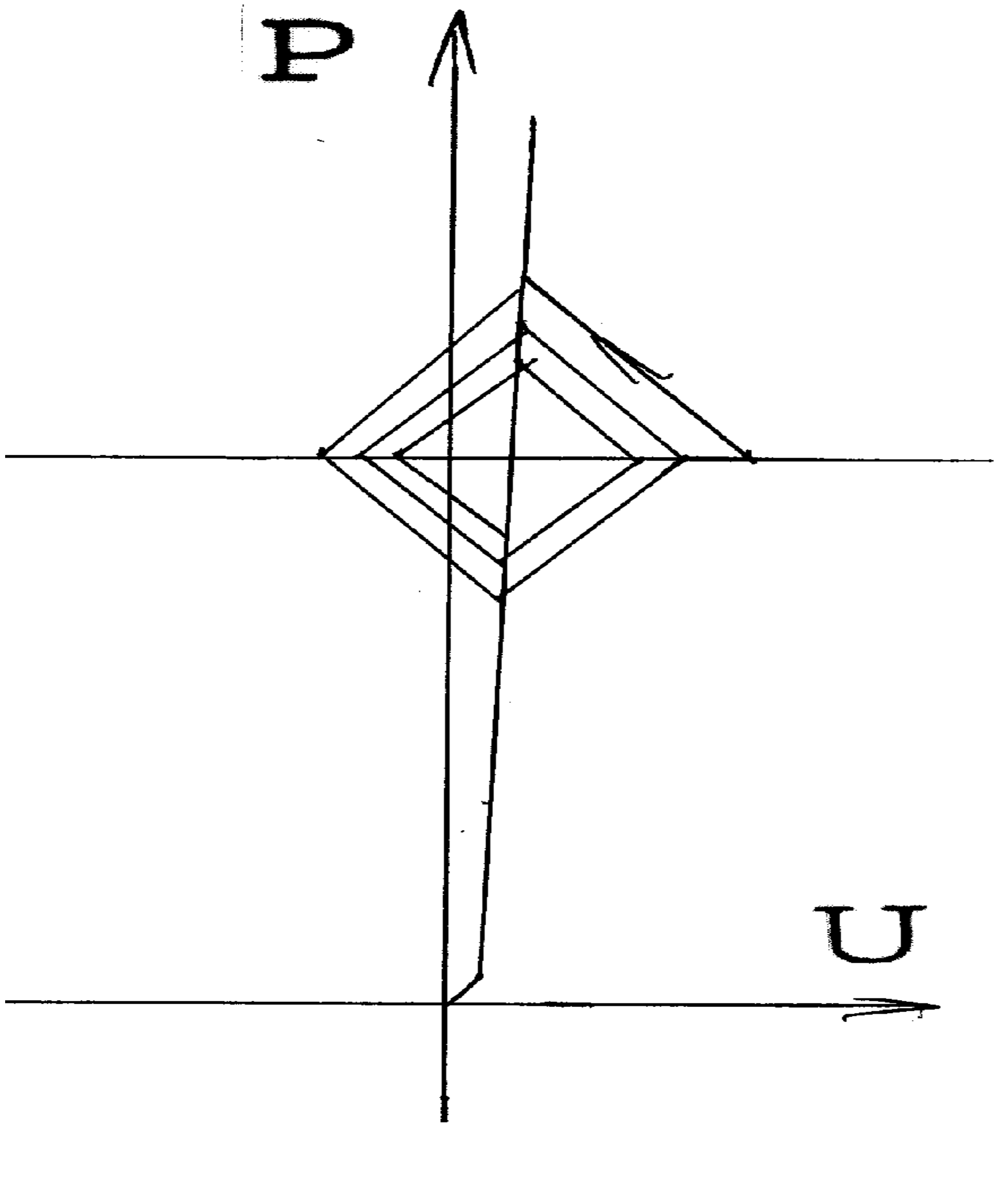
FLUID TRANSIENTS

PREAMBLE

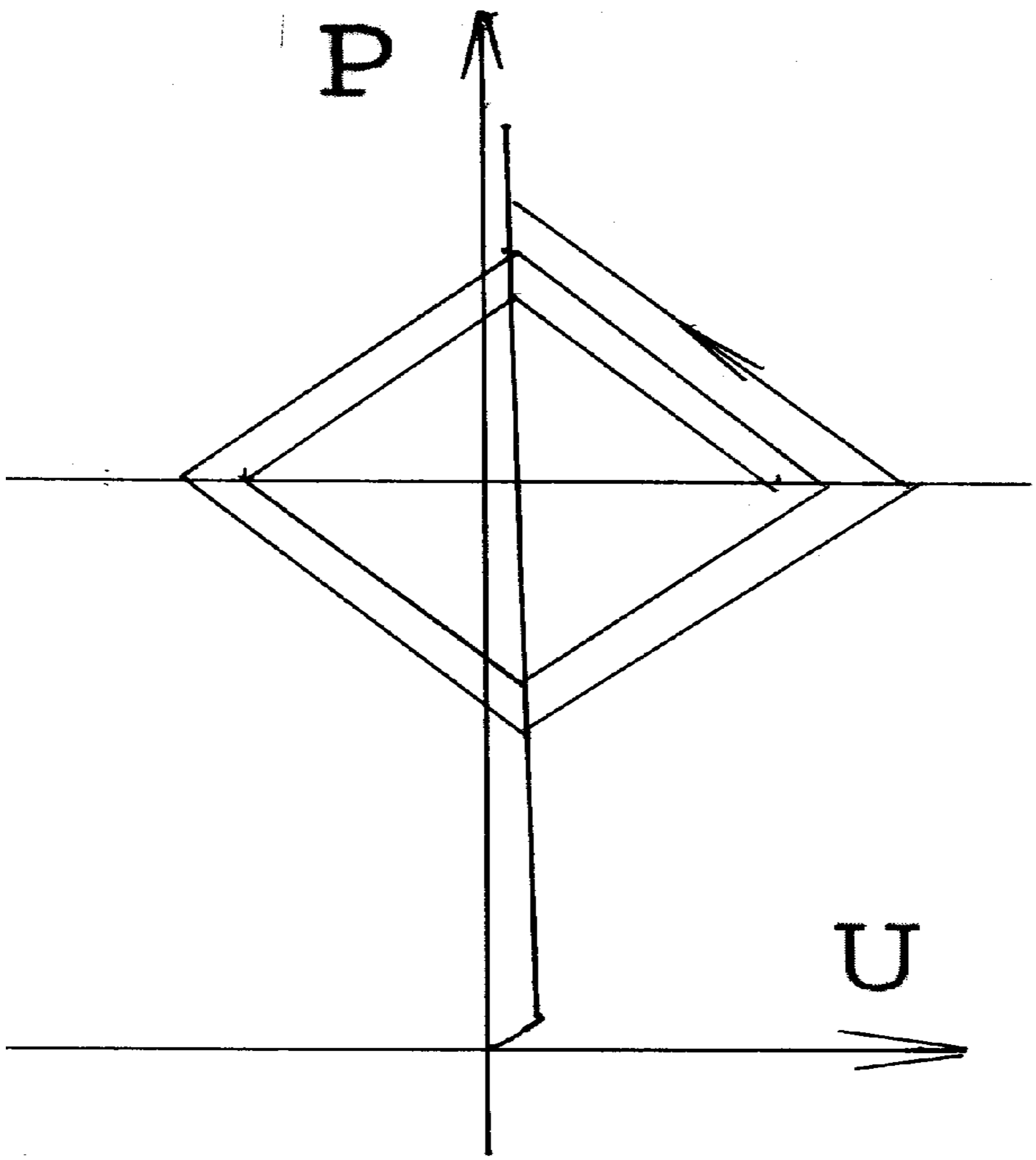
Unsteady flow in pipe networks can be caused by a number of factors. A turbomachine with blades can send pressure waves down a pipe. If the period of these waves matches a natural period of the pipe wave speed resonance develops. A piston pump can send similar waves down a pipe. One way to avoid resonance is to change the wave speed of the pipes in the network. For liquids, one can do this by adding a gas such as air. This can be bled into the network at critical locations or it can be held in a flexible tube which runs inside the pipes. One could also use a flexible pipe to change the wave speed. Sudden valve or turbomachine changes can send waves up and down pipes. These can cause the pipes to explode or implode. In some cases interaction between pipes and devices is such that oscillations develop automatically. Examples include oscillations set up by leaky valves and those set up by slow turbomachine controllers. One way to lessen the severity of transients is to use gas accumulators. Another way is use of relief valves. These are spring loaded valves which open when the pressure reaches a preset level. For high pressure liquids, they create a pathway back to a sump. For low pressure liquids, they allow a gas such as air to enter the pipe. Bypass valves and check valves can be used to isolate turbomachines when they fail.

LEAKY VALVES

A stable leaky valve is basically one that has a pressure versus flow characteristic which resembles that of a wide open valve. This has a parabolic shape with positive slope throughout. An unstable leaky valve has a characteristic that has a positive slope at low pressure but negative slope at high pressure. The flow rate just upstream of a valve is pipe flow speed times pipe area. The flow rate within the valve is valve flow speed times valve area. In a stable leaky valve, the areas are both constant. The valve flow speed increases with pipe pressure so the pipe flow speed also increases. In an unstable leaky valve, the flow speed within the valve also increases with pipe pressure but the valve area drops because of suction within the valve. The suction is generated by high speed flow through the small passageway within the valve. It pulls on flexible elements within the valve and attempts to shut it. In the unstable case, greater suction is needed each time a backflow wave comes up to the valve because the flow requirements of the valve keep getting bigger. In the stable case, less suction is needed because the flow requirements keep getting smaller.



STABLE LEAKY VALVE



UNSTABLE LEAKY VALVE

WAVE SPEED

Consider a wave travelling up a rigid pipe. In a reference frame moving with the wave, mass considerations give

$$\rho\ A\ (S+a) = (\rho+\Delta\rho)\ A\ (S+\Delta S+a)$$

where ρ is density, A is pipe area, S is flow speed and a is wave speed. When a >> S, this reduces to

$$\rho\ \Delta S = -\ a\ \Delta\rho$$

Momentum considerations give

$$[(\rho+\Delta\rho)A(S+\Delta S+a)\ (S+\Delta S+a)\ -\ \rho A(S+a)\ (S+a)] = [P - [P+\Delta P]]\ A$$

$$\rho A(S+a)\ [(S+\Delta S+a)\ -\ (S+a)] = -\ \Delta P\ A$$

where P is pressure. When a >> S, this reduces to

$$\rho\ a\ \Delta S = -\ \Delta P$$

Manipulations give

$$a = \sqrt{\ [\Delta P/\Delta\rho]}$$

For a gas, thermodynamics shows that

$$\Delta P/\Delta\rho = k\ R\ T$$

where k is the ratio of specific heats, R is the gas constant and T is the absolute temperature of the gas. So wave speed becomes

$$a = \sqrt{[k\ R\ T]}$$

For a liquid, fluid mechanics shows that

$$\Delta P/\Delta\rho = K/\rho$$

where K is the bulk modulus of the liquid. It is a measure of its compressibility. So wave speed becomes

$$a = \sqrt{[K/\rho]}$$

For a flexible pipe

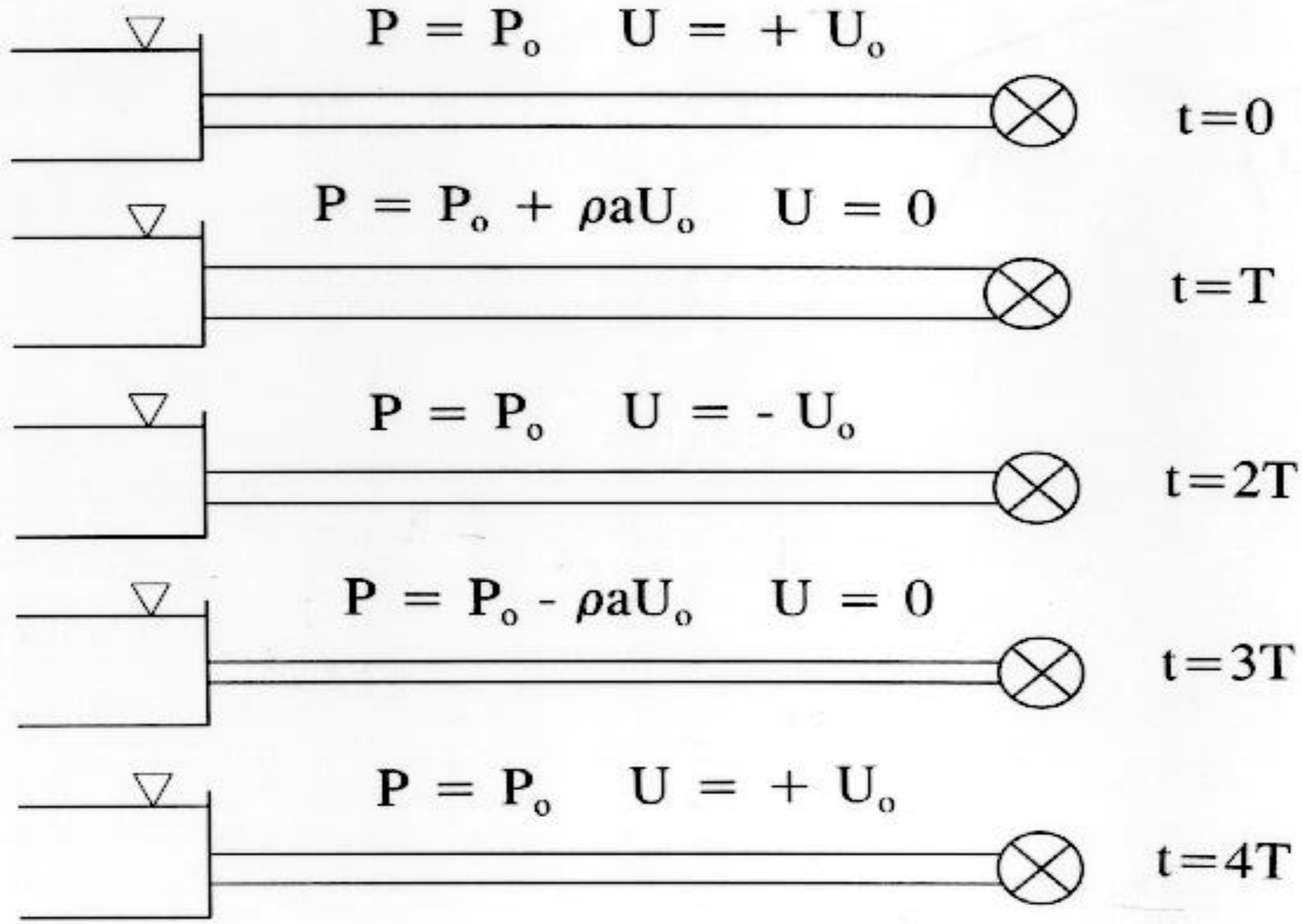
$$a = \sqrt{[\mathbf{K}/\rho]}$$

$$\mathbf{K} = K / [1 + [DK]/[Ee]]$$

where E is the Elastic Modulus of the pipe wall material, e is the wall thickness and D is the pipe diameter.

SUDDEN VALVE CLOSURE

Consider a pipe with a valve at its downstream end and a reservoir at its upstream end. On a ship, the reservoir could be a storage tank. When the valve is suddenly closed, a high pressure wave propagates up the pipe. As it does so it, it brings the fluid to rest. When the wave reaches the reservoir, there is a pressure imbalance. This causes a back flow which propagates as a wave down the pipe. As this wave moves down the pipe, the pressure is restored to its original level. When the wave reaches the valve, there is flow imbalance. This causes a low pressure wave to propagate up the pipe. As it does so, it brings the fluid to rest. When the wave reaches the reservoir, there is a pressure imbalance. This causes an inflow which propagates as a wave down the pipe. As the wave moves down the pipe, the pressure is restored to its original level. When the wave reaches the valve, conditions in the pipe are the same as they were at the instant the valve was closed. So one cycle of vibration requires 4 transits of the pipe by pressure waves. This means that the natural period of the pipe is 4 times the length of the pipe divided by the wave speed: $T = 4L/a$. Measuring T allows one to find the wave speed of the pipe: $a = 4L/T$.


P = P_o U = + U_o
t=0
P = P_o + ρaU_o U = 0
t=T
P = P_o U = - U_o
t=2T
P = P_o - ρaU_o U = 0
t=3T
P = P_o U = + U_o
t=4T