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MECHANICAL ENGINEERING AND MECHANICS DEPARTMENT

PHILADELPHIA, PENNSYLVANIA 19104

April 15, 1974

FINAL REPORT

FOR

AN ASSESSMENT OF TRANSIENT HYDRAULICS PHENOMENA AND ITS CHARACTERIZATION

Richard W. Mortimer

April 1, 1973 to January 30, 1974

NASA Grant NGR 39-004-051

I

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ABSTRACT

The purpose of this report is to present the results of a study supported by NASA Grant NGR 39-004-051. The primary goal of this study was to perform a systematic search of the open literature with the purpose of identifying the causes, effects, and characterization (modelling and solution techniques) of transient hydraulics phenomena.

NOMENCLATURE

b = conduit wall thickness

C = propagation velocity (defined on page 2)

C_1 = (See page 4)

D = diameter of conduit

E = modulus of elasticity of conduit material

F,G = frictional loss coefficients

g = gravitational acceleration

K = bulk modulus of elasticity of fluid

p = pressure

r = radial coordinate

t = time

u = axial velocity

v = radial velocity

x = axial coordinate

γ = specific weight

μ_o = mean absolute viscosity

ν = poisson's ratio for conduit material

I INTRODUCTION

This report presents the results of a study which included the systematic search of the open literature with the purpose of identifying the causes, effects, and characterization (modelling and solution techniques) of transient hydraulics phenomena.

The first section of this report includes the governing partial differential equations which were found to be used in the majority of the papers and some basic definitions which we are utilizing in this study. The second section in this report includes the detail survey sheets in which the type of hydraulics problem, the cause, the modelling, the solution technique utilized, and the existence of experimental verification (if any) are presented for each paper. The third section lists the references used in our study; the fourth, the list of source documents, and the final section contains a discussion of our study.

II DEFINITIONS AND THEORY

This section contains the basic definitions of certain engineering terms which are applicable to the study of hydraulic transients. In addition, the basic governing differential equations utilized in the majority of the papers we reviewed are listed for easy reference.

A. Definitions

Periodic Flow	-- synonomous with steady oscillatory flow
Pulsatile Flow	-- synonomous with steady oscillatory flow
Steady-Oscillatory Flow	-- flow conditions identically repeated in every fixed time interval called the period of oscillation
Steady Flow	-- no change in conditions with time at a point
Transient Flow	-- unsteady flow condition when flow changes from one steady-state condition to another steady-state condition
Unsteady Flow	-- conditions at a point change with time
Waterhammer	-- transient flow in pipelines; rapid deceleration of flow caused by closure of flow passage

B. Theory

The governing equations utilized in the majority of the publications we reviewed can be placed in three categories depending on the degree of approximation used in the model.

1. Simple Model with no Losses

$$\frac{\partial u}{\partial x} = -\frac{1}{\rho C^2}\frac{\partial p}{\partial t} \qquad \text{Continuity}$$

$$\frac{\partial p}{\partial x} = -\rho\frac{\partial u}{\partial t} \qquad \text{Momentum} \tag{1}$$

2. Linear or Quadratic Friction Model

$$\frac{\partial u}{\partial x} = -\frac{1}{\rho C^2}\frac{\partial p}{\partial t} \qquad \text{Continuity}$$

$$\frac{\partial p}{\partial x} = -\rho\frac{\partial u}{\partial t} + R(u) \qquad \text{Momentum} \tag{2}$$

where $R(u) = Fu$ for linear friction model; generally used for laminar flow

Gu^2 for quadratic friction model; generally used for turbulent flow

3. Viscous Model

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial r} + \frac{v}{r} = -\frac{1}{\rho C^2}\frac{\partial p}{\partial t} \qquad \text{Continuity}$$

$$\frac{\partial p}{\partial x} = -\rho\frac{\partial u}{\partial t} + \mu_o\left[\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r}\right] \qquad \text{Momentum} \tag{3}$$

In equations (1), (2), and (3) the expression for the propagation velocity C, is

$$C^2 = \frac{1}{\frac{\gamma}{g}\left(\frac{1}{K} + \frac{DC_1}{Eb}\right)} \tag{4}$$

where C_1 is a parameter which incorporates the flexibility and support of the conduit or pipe. For example, if the flexibility of the pipe is deemed unimportant $C_1 = 0$. Other expressions for C_1 are, for example,

$C_1 = 1 - \nu^2$	for the case where the conduit is anchored against longitudinal movement
$C_1 = 1 - \nu/_2$	for the case where conduit contains expansion joints

The question of which of these theories to use for a particular problem is of much relevance. A recent paper by Goodson and Leonard (GO:72.0) presents a review of some work in fluid line transients and develops a criterion for choosing the particular system of governing equations necessary for a particular problem.

The solution techniques utilized in the majority of the papers included exact integration, graphical, method of characteristics, finite differences and transforms. A recent paper by Streeter (ST:72.0) presents a review of the method of characteristics and center implicit finite difference techniques as applied to transient flow problems.

III SURVEY

This section includes our comments on each of the papers we reviewed. We have four categories of papers; transient, components, periodic, and cavitation. For each paper, we state the cause of the particular phenomena being studied (if discussed), the mathematical modelling and solution techniques utilized, existence of experimental verification (if performed), and any special comments we believe to be relevant.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING		EXPERIMENTAL EVIDENCE	COMMENTS
			ASSUMPTIONS	SOLUTION TECHNIQUE		
LA:98.0 (R24)	Transient	Waves in liquid-tube.	1 Dim. membrane shell; 2-Dim., non-viscous fluid.	Dispersion with long wavelengths.	No	Extension of Korteweg work in Annalen der Physik und Chemie, Vol. 9, Folge, Band 5, 1878, pp 525-542. Lamb's work one of the first to utilize Dynamic Elasticity and fluids.
JO:04.0	"	Water Hammer	1 Dim. theory for wave speed and pressure increase.	Classical Integration.	Yes	Applied Lamb's and Korteweg's work to problem of waterhammer. Discusses wave speeds, pressure increase, effects of closure time, relief chambers, and use of waterhammer to detect holes and air pockets in pipelines.
AL:03.0	"	Water Hammer	Classical 1 Dim. Theory.	Graphical Based on wave solution.		Applied work to design of water works' systems.
WA:33.0	"	Water Hammer	Classical 1 Dim.	Most amenable technique was method of characteristics with graphical solution.	Yes	Symposium on water hammer sponsored by ASME.
KE:29.0	"	Value closure	Classical 1-Dim. Theory.	Several techniques	Some	Rate of gate travel shown to be important.
AN:37.0	"	"	Classical 1-Dim. Theory.	Graphical	No	Method based on work of Allievi.
LE:37.0	"	"	1-Dim. with friction		Yes Reasonable agreement.	Mainly concerned with resurge period.
BE:61.0	"	"	1-Dim. with friction	Graphical		Summaries of graphical work.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING ASSUMPTIONS	MODELLING SOLUTION TECHNIQUE	EXPERIMENTAL EVIDENCE	COMMENTS
KN:37.0	transient	"	1-Dim. Theory with friction.	Graphical Techniques of Bergeron and Angus utilized.	No	Design of self acting shut off valves to limit water hammer effects.
SC:37.0	"	Pump shutdown	1-Dim. Theory	Graphical techniques	Some	Applied to pump shut-down including check valves.
WO:37.0	"	Water Hammer	1-Dim. Theory with linear friction.	Heaviside operational	No	Paper demonstrates applicability of operational calculus.
AN:39.0	"	"	1-Dim. Theory with friction at discrete points.	Graphical work of Allievi.	No	Compound and branched Pipes.
DA:39.0	"	"	1-Dim. Theory	Review of graphical work of Allievi, Bergeron, etc.		Conduits, compound, branched, pump, and air chambers.
RI:39.0	"	"	1-Dim. Theory with linear friction.	LaPlace-Mellin transform.	No	Improvement on Wood's (WO:37.0) work.
SQ:49.0	"	Pump variations				Review and design paper
LU:50.0	"	Oil line surges	1-Dim. with friction	Transform	No	
BI:51.0	"	Valve closure	1-Dim with friction (linear).	Transform	No	Similar to work of Wood (WO:37.0) and Rich (RI:39.0)
PA:53.0	"	Water Hammer	1-Dim. with and without friction.	Analog and digital computers.	No	Apparently first paper utilizing computers for water hammer.
MO:55.0	"	"			No	Review of phenomena, 1-Dim. theories, and surge relief mechanisms
CH:56.0	"	Hydraulic control	1-Dim. with friction	Transforms	No	

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING		EXPERIMENTAL EVIDENCE	COMMENTS
			ASSUMPTIONS	SOLUTION TECHNIQUE		
NI:66.0	transient	"	Same as SK:60.0 with some thick shell terms included.		No	
ST:67.0	"	"	1-Dim. with friction	See comments	No	Distribution piping sy tems. Application of previous Streeter worl to complex systems.
FR:68.0	"	"	2-Dim. inviscid, compressible fluid; shell theory with transverses shear and rotary inertia.	Finite Hankel transform and method of characteristics.	No	Additional stresses shown to develop in shell due to Water Hammer.
KA:68.0	"	"				IN RUSSIAN.
CH:68.0	"	"	1-Dim. theory	Fourier series using analog.		Similar to GO:63.0 wor except for truncation technique (and series
WO:69.0	"	Water Hammer with line motion.	1-Dim. theory with lumped mass-spring damper to simulate line motion.	Algebra	Good comparison	Line motion appears to be important.
BR:62.0	"		2-Dim. fluid, rigid walls; laminar flow.	LaPlace Transform	No	Operators developed.
GO:63.0	"	Hydraulic line dynamics.	1-Dim. with friction	Transform with quotient of infinite products.	Good over freq. range appropriate to assumptions.	
AN:66.0	"	Hydraulic line dynamics.	1-Dim. with and without friction.	LaPlace transform.		More closed form solutions by Martin.
ST:68.0	"	"	Apply Lattice of 1-Dim. pipes to 2D 3-D Lattice	Method of characteristics with computer	No	See ST:67.0

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING		EXPERIMENTAL EVIDENCE	COMMENTS
			ASSUMPTIONS	SOLUTION TECHNIQUE		
SK:56.0	transient	Water Hammer	2-Dim. inviscid fluid and Flugge shell equations.	Laplace and Fourier Transforms.	Confirmation of some theory.	See conclusions of this paper for discussion of wavelength effects, etc.
RO:60.0	"	Valve closure	1-Dim. with linear linear friction.	Separation of variables.and series solution.	Reasonable comparisons.	Viscous fluid applications.
WA:60.0	"	Water Hammer	1-Dim. Navier Stokes with longitudinal viscosity.	Separation of variables.	No	Viscous dispersion. Results show viscosity effects rise time and pulse shape; not magnitude.
HA:63.0	"	"	1-Dim.			Wave velocities for different pipe properties and supports.
LI:63.0	"	Nuclear blast wave	Classical 1-Dim.	Superposition of waves for various support conditions.	Yes	
ST:62.0 *	"	Water Hammer	1-Dim. with non-linear friction.	Method of characteristics with computer.	Good agreement	Solves many boundary value problems. Claim of originality disputes by Paynter. See Refs. in this paper.
ST:63.0	"	Valve stroking design.	1-Dim. with non-linear friction.	Method of characteristics with computer.		Application of work in ST:62.0 for valve closure specification to limit effect of water hammer.
CO:65.0	"	Water Hammer	1 Dim. with non-linear friction with minor losses lumped at boundary	Method of characteristics. See ST:62.0 and ST:63.0.	Good agreement	Reflections of primary concern.
KA:65.0	"	"	1-Dim.	Wave superposition	No	Applied to pipe junctions.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING ASSUMPTIONS	MODELLING SOLUTION TECHNIQUE	EXPERIMENTAL EVIDENCE	COMMENTS
DS:62.0	transient	Hydraulic line dynamics	2-Dim. with friction laminar, compressible	LaPlace Transform	Reasonable agreement.	Small diameter pipe applications.
JA:49.0	"	Sound waves in liquid-filled cylinders.	2-Dim. non-viscous	Dispersion (harmonic) analysis	Good agreement	For higher frequency problems. Wave length order of pipe diameter. Many boundary conditions.
TH:51.0	"	"	2-Dim. viscous, membrane shell theory.	Dispersion (harmonic) analysis	No	Adds to work of LA:98.0 and JA:49.0.
BI:52.0	"	"	2-Dim. fluid; 3-Dim. elasticity.	Dispersion (harmonic) analysis	No	For wavelength to diameter ratio >5, Water Hammer wave velocitie are applicable.
FA:52.0	"	"	Love Theory	Dispersion (harmonic) analysis	Yes	
LI:56.0	"	"	2-Dim. inviscid fluid; shell with transverse shear and rotary inertia included.	Dispersion (Harmonic) analysis		Major difference between this paper and TH:51.0 is improved shell theory.
SC:59.0	"	Pneumatic line dynamics.	1-Dim., linear friction laminar, no pipe effect on wave velocity.		Reasonable agreement.	See discussion and Ref. 6.
•KE:56.0	"		1-Dim.		Yes	Mainly experimental demonstration. Concrete pipe.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING ASSUMPTIONS	MODELLING SOLUTION TECHNIQUE	EXPERIMENTAL EVIDENCE	COMMENTS
CO:72.0	Transient	For hydraulic mining.	1-Dim. with non-linear friction	Method of characteristics.		
GO:72.0	"	Fluid line transient survey.				Good Reference list,* Lists criteria for choosing appropriate models. Weak on description of other than operator type solutions.
JO:72.0	"	Hydraulic line dynamics.	1-Dim. with boundary motion prescribed.	Method of characteristics and closed form solutions.	Comparison with both types of solutions.	Method of characteristics gives best solution.
ST:72.0	"	"			No	Review of method of characteristics and center implicit finite difference techniques, discussion of stability, accuracy, and numerous boundary conditions.
YO:72.0	"	Natural gas line dynamics.	One-Dim. with non-linear friction.	Method of characteristics.	No	Discussion of error and stability criteria (method of characteristics).
FU:72.0	"	Orifice and short line transients.	1-Dim., inviscid compressible.	Closed form and stepwise plane wave solutions	Good agreement	

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING		EXPERIMENTAL EVIDENCE	COMMENTS
			ASSUMPTIONS	SOLUTION TECHNIQUE		
MA:73.0	Transient	General				Good review of recent work in Europe. Total of 218 papers cited (mainly European).
ME:73.0	"	General	Viscous, compressible turbulent, 1-Dim., constant friction, non-linear.	Operational calculus, linearization yield transfer matrix.		One of few papers addressing turbulent flow. Follows BR:69.0.
SH:73.0	"	General	1-Dim. Model		Demonstrates: 1. dependence of friction on freq. 2. shear stress at wall function of R and freq. 3. in general, friction factor determined by steady flow not adequate for transient analysis, 4. inertia effects important.	Basically experimental paper.
BR:69.0	"	"	2-Dim. Model, turbulent, breaks into 3-frequency regimes.	Semiempirical with much transform.	Yes	Read conclusions
JA:72.0	"	Water Hammer	2-Dim. Navier Stokes compressible.	Separation of variables and transform.	No	Theory predicts growth of boundary layer both in time and space.
MO:73.0	Transient	Blow down or flow stoppage.	1-Dim., non-linear friction.	Method of characteristics.	Comparison with existing experiments.	Major emphasis in paper is to predict pipe reaction forces.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING ASSUMPTIONS	MODELLING SOLUTION TECHNIQUE	EXPERIMENTAL EVIDENCE	COMMENTS
BI:73.0	Transient					Describes technique for correcting data obtained from transient measurements.
TH:69.0	"					Essentially identical to LI:56.0
BR:69.0	"	General	Laminar, 1-Dim., compressible.	Method of characteristics.	No	Extension of Zielke's work (ZI:68.0). Extension of method of characteristics to include "Quasi-hyperbolic" equations.
MA:68.0	"	Pneumatic transients.	1-Dim., non-viscous	Method of characteristics.	No	Duplicates much of the work of Benson, et al (Int. Jnl. of Mech. Sci., Vol. 6, No. 1, 1964).
HO:67.0	"	General	Theory of BR:62.0 and DS:64.0; includes viscous shear.	LaPlace Transform	Exp. verifies validity of 1-Dim. model with freq. dependent shear.	
ZI:67.0	"		1-Dim. with friction.	Method of characteristics.	Good correlation with theory. Shows freq. dependency of friction predicts distortion of pulses in pipes	Extension of work in HO:67.0.
GE:67.0	"	"	Navier Stokes equations.	Potential (scalar and vector) decomposition; Laplace transform and phase velocity.	Verfied modes of propagation	Notes the effect of elastic walls on spattial propagation of modes.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING		EXPERIMENTAL EVIDENCE	COMMENTS
			ASSUMPTIONS	SOLUTION TECHNIQUE		
KR:66.0	transient	General	Classical 1-Dim. water hammer equation including friction.	Method of characteristics.	No	Not a very good literature search in this paper; most work already done.
DO:66.1	"	"	Classical 1-Dim. Water Hammer eqtn. including friction.	Wave plan-similar concept to method of characteristics.	Yes	Incorporates a distributed parameter method.
DO:66.0	"	"				Same as DO:66.1
DS:64.0	"	General	2-Dim; Navier-Stokes for small diameter tubes.	Laplace Transform; produces transfer matrix	Good comparison between theory and experiment.	
RE:60.0	"		1-Dim., non-viscous, non-linear eqtns.	Phase velocity	Yes	Dynamic response of long hydraulic lines.
GO:64.0	"	"	1-Dim. Water Hammer Theory.	Laplace transform and infinite products to produce transfer functions.	Good agreement with theory.	
TA:65.0	"	"	Theory of LI:56.0	Fourier transform for steady state; method of characteristics for transient	No	
GO:62.0	"	"	1-Dim. Water Hammer	Transform to produce transfer function.	Good agreement with theory.	
OL:62.0	"	Hydraulic turbine gate oscillations.				Frequency response tests on hydraulic turbines.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING		EXPERIMENTAL EVIDENCE	COMMENTS
			ASSUMPTIONS	SOLUTION TECHNIQUE		
LE:52.1	Components	Steady-state axial force on control valve pistons.	Non-viscous and incompressible; 2-Dim. flow; flow assumed quasi-irrotational.	See paper	Good Agreement	For servo-mechanisms.
LE:52.1 (RR 03)	"	Valve instability	1-Dim. force (transient) balance on valve.	"	Good Qualitative Agreement.	
ST:53.0	"	Relay servo mechanism effects of friction.	See paper	"	No	Reasonably large reference list.
WE:56.0	"	Frequency response of servomechanism designed for optimum transient response.	"	"	No	Incorporate serme control (control signal proportional to norma stab. signal and sign-error-root-modulus-error signal).
EZ:57.0 (RR 04)	"	Analog and digital simulation of conduits, valves, pumps in hydraulic and Pneumatic syste system.	"	"	No.	Applications to water-hammer; air chamber and check valve in pumping plant; contro of flows and levels.
BU:59.0	"	Loaded hydraulic integrating relay.	Pressure of oil supply is constant; transmission of pressure thru oil is instantaneous; no dilatation of hydraulic circuit occurs due to oil pressure.	Closed form integration.	No	Considers response of loaded hydraulic rela to stop function, ram function sinusoidal, and general inputs.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING: ASSUMPTIONS	MODELLING: SOLUTION TECHNIQUE	EXPERIMENTAL EVIDENCE	COMMENTS
IS:63.0	components	Self-excited oscillation of hydraulic values.	fluid is incompressible, laminar, flows along surface of spool; pressure drop due to viscosity is lumped.	Closed Form Integration	Yes	
WA:63.0	"	Electrohydraulic servomechanisms	See paper	See paper	No	Design for servo with near time-optimal responses (DA:65.1).
DA:64.0	"	Hydraulic servomechanisms with non-linear value flow characteristics.	See paper	Power series expansion.	No	
DA:64.1	"	Hydraulic servo mechanism connected to inertial load.	Effects of inertia load compressibility leakage structural flexibility and da damping, coulomb friction included.	Analog	Yes	
NI:64.0	"	Loaded high pressure hydraulic on-off servo.	See paper	Transform	Yes	Components include valve, cylinder, ampli fier, relays, potentic meter, load, oil.
DA:65.0	"	Servo with time optimum transient response valve.	See paper	Closed form Integration	No	Design (DA:65.1)
CH:66.0	"	Value controlled actuator.	Classical valve controlled actuator with compressibility of fluid included.	Graphical	No	
MA:70.0	"	Hydraulic servo with unsymmetrical oil volume conditions.	Small perturbation theory with coulomb friction included.	Analog		

ARTICLE RE[redacted]ENC[redacted] NUMBER	[redacted]LAS[redacted]CAT[redacted]	[redacted]AUSES	MODELLING ASSUMPTIONS	SOLUTION TECHNIQUE	EXPERIMENTAL EVIDENCE	COMMENTS
AL:37.0	components	Value closure. Air chamber design.	1-Dim, with and without friction.	Finite differences	No	
AN:37.0	"	Valve, pump failure Air chamber and value design	Classical 1-Dim., no friction; see AL:03.0.	Graphical	No	
WO:70.0	"	Air chamber design	Distributed parameter 1-Dim.	Wave plan	Good correlation	
KA:73.0	"	Fluid transmission line.	Navier Stokes perturbation eqtns.	Transform	Good correlation	
GO:67.0	"	Hydraulic control system.	3rd order linear system.	-	No	
GE:67.0	"	Hydraulic conduits		-	Good correlation	Review of state-of-th art for modelling hydraulic lines as related to fluid contro systems.
NI:62.0	"	Pneumatic transmission lines.	Navier Stokes	Harmonic	No	
KE:73.0	"	Hydraulic actuators design model			No	
BE:72.0	"	Pneumatic pulse transmission.			Yes	Mainly exp. study to study effect of tube size and fittings on pulse distortion and a attenuation.
GO:68.0	"	Differential pulse-length modulated penumatic servo utilizing floating flapper-disk switching value.			Yes establishes validity of this concept.	Mainly a feasibility Study.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING		EXPERIMENTAL EVIDENCE	COMMENTS
			ASSUMPTIONS	SOLUTION TECHNIQUE		
TU:59.0	components	Response of loaded hydraulic servo-mechanism.	Fluid incompressible pressure drops occur only at piston of actuator and control ports of valve.	See paper	No	Good literature review.
EZ:60.0 (R 16)	"	Lumped parameter modelling of fluid-power systems.		"	No	Fluid inertance, capacitance, and resistance are primary lumped parameters.
DA:63.0		Response of hydraulic servomechanism with inertial load.	Coulomb damping, leakage, and compressibility effects are included.	Analog solution	Reasonable agreement for risetime, frequency and damping ratio of transient oscillation.	

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING ASSUMPTIONS	MODELLING SOLUTION TECHNIQUE	EXPERIMENTAL EVIDENCE	COMMENTS
IT:73.0	components	Pipe Junctions	Empirical		Yes-to verify empirical formulas for loss factors. in tees.	
KE:69.0	"	One-way air chambers for pumping plants.	Water column theory	Finite Difference	No	

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING: ASSUMPTIONS	MODELLING: SOLUTION TECHNIQUE	EXPERIMENTAL	COMMENTS
DI:29.0 (RR38)	Periodic	Periodic surges caused by action of reciprocating pumps Also covers surges resulting from ca-	Line-pump resonance viscous damping 1-D wave speed eqtn. and pressure velocity relation.	Mostly graphical analysis.	Laboratory and in field setups studied by investigators and various pipe line companies recommends air chambers as most satisfactory solution to surge problems.	Emphasis on theory application to eliminate surge problem in oil pipelines.
IB:50.0 (R32)	Periodic	Oscillatory pressure variation applied to one end of a tube.	Elementary theory developed and then expanded to include compressibility finite pressure amplitudes, fluid acceleration, end effects and heat transfer.	Mathematical analysis often employing Bessel's functions (Harmonic analysis, basically).	Nc	For instrument lines connecting a tube (with pressure variation) to a pressure-sensitive element.
WE:66.0 (R40)	Periodic	Pulsating flow for power transmission		Impedance method: lumped and distributed parameter.	Experiments were made to study the effects of pulsating flow on line dynamics and viscosity effects.	
BL:62.0 (R44)	Periodic	Oscillating upstream valve	Undamped sinusoidal waves neglect waves in pipe wall fluid velocity<<sonic velocity termination impedance known as function of frequency pipeline vibrations described as perfect viscous damped spring-mass system.	Transfer functions lumped parameter.	Good agreement between theory & experiment on a flexible line with a 90° elbow.	Shows that the effect of line motion on fluid wave pattern is considerable.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING: ASSUMPTIONS	MODELLING: SOLUTION TECHNIQUE	EXPERIMENTAL EVIDENCE	COMMENTS
WO:68.0 (M 39)	Periodic	Sinusoidal and non-sinusoidal inputs caused by varying output orifice oe opening and by a side branch piston.	Spring-mass analogy	Digital nonlinear and closed form linear analysis transfer functions (distributed parameter wave plan).	Experimental results in agreement with predicting.	
KA:67.0	Periodic	Pressure waves in propellant feed	Flugge's shell equations 2-D Eqations of motion for compressible, inviscid fluid.	Harmonic		See Herrman & Mirsky's work, also, good discussion on which types of excitation will require higher levels of theory.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING ASSUMPTIONS	MODELLING SOLUTION TECHNIQUE	EXPERIMENTAL EVIDENCE	COMMENTS
OR:69.0	Periodic	Fuel systems, biological systems.	Navier Stokes	Periodic and separation of variables. Also perturbation solution.	No	
HA:72.0	Periodic (vibration)	Pump generated pressure pulsations.			Yes	Measurements of reactor vessel and com ponents in three loo water reactor.
CA:69.0	pulsatile	Greater arteries of cardiovascular system.	1-Dim., incomp. Navier-Stokes.	Method of characteristics.	Reasonable correlation.	
IT:69.0	" (vibration)	Pneumatic line vibrations.	1-Dim.	Harmonic	No	

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING		EXPERIMENTAL EVIDENCE	COMMENTS
			ASSUMPTIONS	SOLUTION TECHNIQUE		
GA:58.0 (RR 33)	Cavitation	Column separation due to pressure reaching vapor pressure in line. Due to valve closure	Classical 1-Dim. Theory incl. effect of negative pressure sur surge due to column separation.	Closed form Integration	reasonable agreement with Theory; qualitatively demonstrates effect of secondary waves.	
DU:73.0 (RR 21)	"	Column separation due to pressure reaching vapor pressure in line. Due to valve closure	None	None	Experimental verification of effects of flow separation on pressure pulses in hydraulic system.	
LI:62.0 (RR 18)	"	Column separation due to pressure reaching vapor pressure in line. Due to valve closure.	1-Dim. "rigid column" theory where liquid is assumed to be in compressible after formation and before closure of vapor column. Neglect of waterhammer effect. The above for <u>motion of liquid column</u>. <u>For spreading of interface face</u>. - 1-Dim. eqtns with friction neglected.	Closed form Integration for motion of liquid column. Method of characteristics for spreading of interface.	No	
CA:64.0 (R 45)	"	Cavitating Pumps	Classical 1-Dim. Theory.	Graphical (characteristics)	reasonable agreement with some analytical results.	Reasonable literature review of cavitation problem. Paper concerned with pump "blow-up" in phosphate slurry lines.
LI:64.0 (RR 19)	"	Column separation due to rapid value closure or power failure.	Classical 1-Dim. Theory, neglect on friction.	Transforms	reasonable agreement.	Prediction of maximum pressure due to cavity collapse is main contribution of paper.
SH:65.0 (R 63)	"	Column separation due to rapid value closure or power failure.		Graphical	Yes	More of an expose of problem rather than solution. Does not includ all references to date.

ARTICLE REFERENCE NUMBER	CLASSIFICATION	CAUSES	MODELLING		EXPERIMENTAL EVIDENCE	COMMENTS
			ASSUMPTIONS	SOLUTION TECHNIQUE		
BA:67.0 (R 42)	Cavitation		1 Dim. with friction	Method of characteristics	Favorable agreement	Method of solution i computerized. Exp. shows that a turbulent, 2-phase flow occurs ahead of the main vapor cavity.
DR:73.0	"		1-Dim. with friction	Method of characteristics	Reasonable agreement for first pressure peak.	Kerosene chosen for study. Primary concern is with air release in a fluid rather than vapor formtion.
BA:73.0	"	Values	Empirical		No	Design for cavitatio in butterfly valves.
MC:72.0	"	On-off servos	See paper			Discusses Effects in on-off controlled Hydraulic servos.

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VI DISCUSSION

Based on the present literature search, certain current research trends and future research needs are apparent. These are as follows:

Current Research Trends

a. increased application of numerical techniques to the solution of the system of differential equations which govern the transient line flows.

b. inclusion of "higher order" effects (e.g. axial and radial effects of the fluid and pipe) in the modelling of the transient phenomena

c. solution of 2 and 3-dimensional transient flow problems

d. studies involving the effects of the boundary layer and nonlinear terms on the transient response have been initiated

Future Research

a. more emphasis on the mathematical modelling of components utilized in hydraulic control systems

b. application of the finite element method to the modelling and solution of transient line flows

c. further computer program development for the analysis of the response of complicated systems to transient flows