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Pipeline vibrations.
Computer program for the prediction of fluid transients in flexible, unbranched three-dimensional piping systems.

Associated software: ESDUpac A9331

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the following Working Party on behalf of the Internal Flow Panel:

Mr E.M. Curtis	— Cambridge University
Dr S.J. Murray	— W.S. Atkins Science and Technology
Mr G.A. Parry	— Mechanical Engineering Centre, GEC Alsthom
Prof. A.R.D. Thorley	— The City University
Prof. A.E. Vardy	— The University, Dundee.

The Internal Flow Panel, which took over the work on internal flow previously monitored by the Fluid Mechanics Steering Group, first met in 1979 and had the following membership:

Chairman	
Dr J.A. Eaton	— University College, Galway, Eire
Members	
Mr D.A. Campbell	— Rolls-Royce Ltd, Derby
Mr J. Campbell	— Ove Arup and Partners
Dr C.J. Clark	— BP International Ltd
Prof. D.H. Freeston*	— Auckland University, New Zealand
Dr M.E. Gill	— W.S. Atkins Science and Technology
Mr A.J. Green	— BHR Group Ltd
Dr A. Johnson	— Schlumberger Cambridge Research Ltd
Prof. J.L. Livesey	— University of Salford
Dr M. Moore	— Independent.

* Corresponding Member

The technical work involved in the assessment of the available information and the construction and subsequent development of the computer program was undertaken by

Dr D. Fan — J.P. Kenny Technology Ltd

(previously a research fellow in fluid/structure interaction at The University, Dundee), with the assistance of

Mr S.J. Pugh — Head of Thermofluids Group

who prepared the ESDUview interface to the program and the Data Item. Mr Pugh had overall responsibility for the work in this subject area.

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PIPELINE VIBRATIONS
COMPUTER PROGRAM FOR THE PREDICTION OF FLUID TRANSIENTS IN FLEXIBLE, UNBRANCHED THREE-DIMENSIONAL PIPING SYSTEMS

ESDU 93031 directly accounts for the mutual coupling between internal preaaure and flow conditions, and the stresses and structural motion of the pipework. The system must consist of straight pipes each of uniform cross-section and material properties and each aligned with one of a set of orthogonal axes. It is assumed that all bends remain right angles and do not flex. Externally-acting rigid supports can be modelled at any location in any or all the three translational and three rotational degrees of freedom. The system can have a reservoir or a centrifugal pump (running at constant speed on running down after a trip) at the upstream end, and a reservoir or a valve (opening, closing or fixed area) at the downstream end. Data on the pump characteristics and rota inertia are required (although default data are included) and allowance may be made for backflow. The valve may be closed instantaneously, with a linear area changed with time, or an area/time closure curve may be input.

Output includes steady-state values, together with maximum and minimum values and their location, of pressure, velocity, pipe displacement, axial and shear forces in the walls, and torsional and bending moments in the walls; the time variation of user-chosen variables at selected locations over the run time can also be provided. Criteria by which it can be established whether structural coupling is important are defined and their use discussed. The program is provided to run within ESDUview, a user-friendly environment for personal computer users.

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PIPELINE VIBRATIONS
Computer program for the prediction of fluid transients in flexible, unbranched three-dimensional piping systems

1. NOTATION AND UNITS

		SI	British
A	cross-sectional flow area of member	m^2	ft^2
A_p	cross-sectional area of member wall	m^2	ft^2
A_v	instantaneous cross-sectional flow area of valve	m^2	ft^2
a	speed of propagation of pressure waves in liquid (wave speed), see Equation (4.4)	m/s	ft/s
a_p	speed of propagation of pressure waves in axial direction in member wall, see Equation (4.5)	m/s	ft/s
C_d	instantaneous non-dimensional discharge coefficient of valve	–	–
D	internal diameter of circular member	m	ft
E	Young's modulus of member wall material	N/m^2	lbf/ft^2
f	local value of (Fanning) friction factor		
f_j	natural frequency of structural vibration mode	Hz	Hz
F	local member force	N	lbf
G	shear modulus of elasticity of member wall material, $G = E/\{2(1+\nu)\}$	N/m^2	lbf/ft^2
h	instantaneous non-dimensional head at pump, $h = H/H_R$	–	–
H	instantaneous head at pump	m	ft
H_P	available head at pump	m	ft
H_R	rated head of pump	m	ft
I	second moment of area of member wall	m^4	ft^4
I_P	mass moment of inertia of rotating components of pump	$kg\ m^2$	$slug\ ft^2$
K	bulk modulus of liquid, see Section 4.3.6	N/m^2	lbf/ft^2
k_l	local loss factor, see Section 4.3.5	–	–
L	member length	m	ft

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m	instantaneous non-dimensional pump torque, $m = M/M_R$	–	–
M	local member bending moment	N m	ft lbf
M_p	instantaneous pump torque	N m	ft lbf
M_R	rated pump torque	N m	ft lbf
n_i	number of segments in member i of pipework model, see Section 4.5	–	–
N_P	instantaneous value of rotational speed of pump	rad/s	rad/s
N_R	pump rated rotational speed	rad/s	rad/s
N_{SS}	steady-state value of rotational speed of pump	rad/s	rad/s
P_R	rated shaft power of pump	W	ft lbf/s
p	pressure in liquid	N/m^2 (Pa)	lbf/ft^2
Q_P	instantaneous volume flow rate of pump	m^3/s	ft^3/s
Q_R	rated volume flow rate of pump	m^3/s	ft^3/s
q	non-dimensional flow of pump, $q = Q_P/Q_R$	–	–
t	flow time, or member wall thickness	s m	s ft
t_c	closure time of valve	s	s
Δt	time step, see Section 4.5	s	s
T	run time, or flow period, for analysis	s	s
T_a	time scale for pressure waves in liquid, see Section 3.2	s	s
T_{fd}	time scale for flow disturbance, see Section 3.2	s	s
T_ω	time scale for dominant mode of structural vibration, $T_\omega = 1/f_j$, see Section 3.2	s	s
u	local member displacement from unpressurised position	m	ft
V	local value of liquid flow velocity	m/s	ft/s
V_0	steady-state flow velocity	m/s	ft/s
V_R	maximum permitted reverse flow velocity through one-way valve at pump outlet, see Section 4.4.2	m/s	ft/s

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x, y, z	in-plane distances between junction and reference coordinate axes in x'-, y'- and z'-direction, respectively	m	ft
x', y', z'	mutually-orthogonal directions in reference coordinate system, see Section 4.3.1	–	–
Δp_d	pressure drop across open or partially-open valve	N/m^2 (Pa)	lbf/ft^2
Δp_f	pressure drop along straight length of member due to member wall friction and local losses	N/m^2 (Pa)	lbf/ft^2
Δt	time increment of model	s	s
ν	Poisson's ratio of member wall material	–	–
ρ	density of liquid	kg/m^3	slug/ft^3
ρ_w	density of member wall material	kg/m^3	slug/ft^3

Subscripts

i	refers to member i (of NM)
P	refers to point value on valve operation characteristic, see Section 4.4.3
0	refers to steady-state flow conditions (*i.e.* prior to initiation of fluid transients)
ref	refers to reference value
w	refers to member wall
x, y, z	refer to global x'-, y'- and z'-axes, respectively, see Section 4.3.1

Additional symbols

The following symbols, in common with the computer program, refer to parameters used to describe the model of the pipework. The parameters of the model are defined in Section 4.1.

NJ	number of junctions in pipework model, $NJ = NM + 1$
NM	number of members in pipework model
$NMIN$	number of segments into which shortest member is divided, see Section 4.5
NV	number of variables recorded for output, see Section 5.3.3
NVP	number of points in valve characteristic representation, see Section 4.4.3

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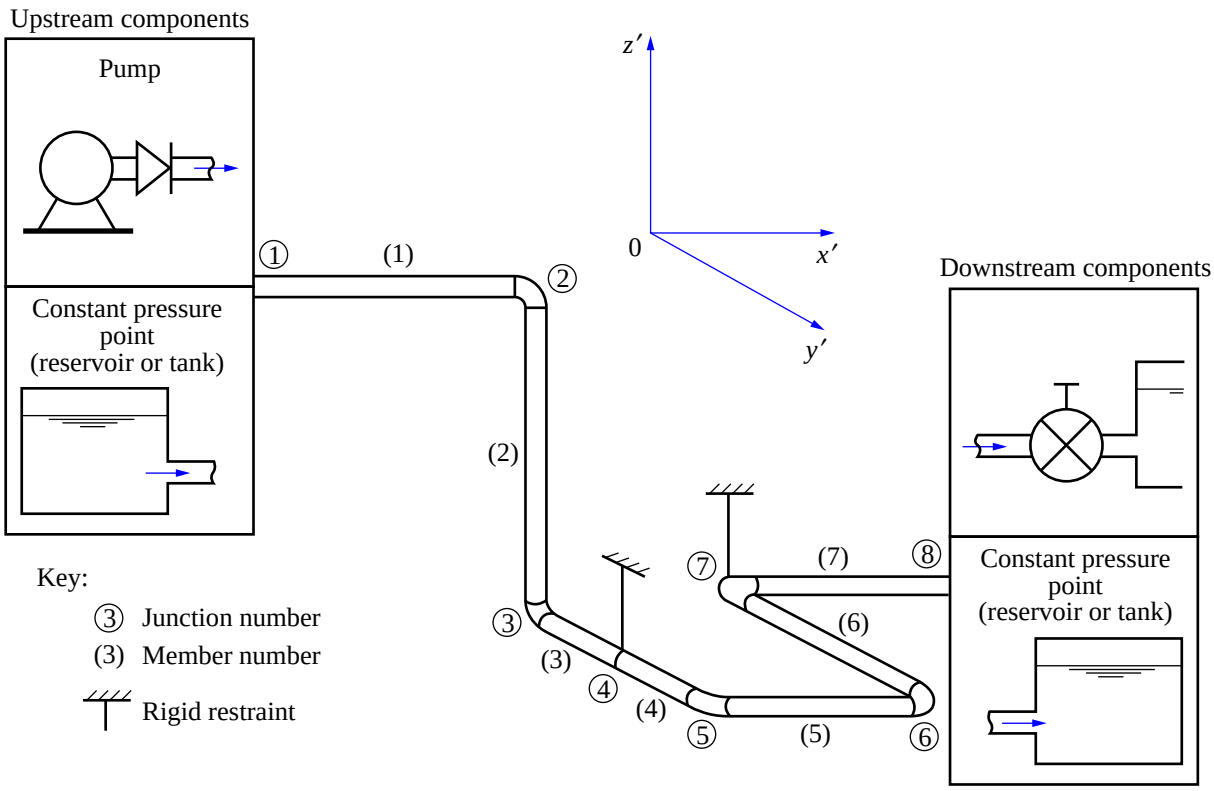
2. INTRODUCTION

2.1 Summary

This Data Item describes a computer program, ESDUpac A9331, for the prediction of fluid transients in flexible, unbranched three-dimensional piping systems running full of liquid. The program performs a one-stage fluid/structure interaction analysis, directly accounting for the mutual coupling between the internal pressure and flow conditions and the stress and structural motion in the pipework. The program is applicable to a range of orthogonal piping configurations, as described in Table 2.1 and shown in Sketch 2.1.

TABLE 2.1 Applicability of ESDUpac A9331

System type	Component at upstream end	Component at downstream end
1	constant pressure point (reservoir)	valve (either closing, opening or with fixed flow area)
2	centrifugal pump, either running at constant speed or tripped (*i.e.* running down)	constant pressure point (reservoir)
3	centrifugal pump, either running at constant speed or tripped (*i.e.* running down)	valve (either closing, opening or with fixed flow area)



Sketch 2.1 Systems to which the program is applicable

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Each straight length of pipe is of uniform cross section and material properties and lies parallel to one of three orthogonal axes. The structural flexibility of the piping system is assumed to arise entirely from the elasticity of the pipes, as all bends remain at 90° and do not flex. Discrete externally-acting rigid supports can be modelled at any chosen location, in any or all of the three translational and three rotational degrees of freedom.

The program calculates steady-state values and time histories of the following parameters.

Flow parameters	**Structural parameters**
– pressures,	– pipe displacements (relative to the unpressurised position),
– velocities.	– axial and shear forces in pipe walls and on supports and hangers,
	– torsional and bending moments in pipe walls and at supports and hangers.

Maximum and minimum values of all of these parameters, calculated over a specified run time, are output by the program.

General background information on fluid/structure interaction in flexible piping systems is given in Section 2.2, and the applicability of other ESDU Data Items to fluid/structure interaction and uncoupled fluid transients analysis is discussed in Section 2.3. Criteria for a fully-coupled fluid/structure interaction analysis are discussed in Section 3. The model of the three-dimensional, flexible piping system upon which the methods of the computer program are based is described in Section 4. Guidance on the use of the program, and on numerical values of the input parameters, is given in Section 5. A worked example in Section 6 illustrates the use of the program.

2.2 Background

Structural vibrations occur in many piping systems following changes in the flow rate, due to valve closure or pump trip for example. The transient pressure changes, or fluid transients, which propagate through the contained fluid following a flow disturbance lead to pressure differences along lengths of pipework and across bends and other components. These pressure differences exert time-dependent forces on the pipework which, in systems that are not rigidly anchored, induce structural motion; this motion in turn affects the pressure and flow of the fluid. Additionally, deformations of the pipe wall resulting from the changes in internal pressure propagate rapidly along the pipe walls as axial stress waves. This phenomenon can lead to large instantaneous changes in pipe wall stresses and further fluctuations in the internal pressure.

In order to obtain reliable estimates of the fluctuating quantities in liquid-filled systems, a method of analysis must be used in which the flow conditions and structural parameters are *fully-coupled* (that is, the mutual coupling between the flow conditions and structural parameters is included). The effects of coupling are generally much less important in gas-filled systems, where the coupling is weaker and can usually be neglected.

Guidance on the mechanisms leading to fluid/structure coupling and on the effects of coupling in the estimation of numerical values of the fluid and structure parameters is given in Section 3.1. The methods of ESDUpac A9331 ensure that all parameters are ***fully-coupled***. A companion program, in which these parameters are partially-coupled, is provided as ESDUpac A8930 and is discussed in Section 2.3.

In the absence of fully- or partially-coupled methods, it has been common industrial practice to use prediction methods in which the fluid and structural parameters are ***fully-uncoupled***. **The use of**

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***fully-uncoupled* analysis methods for flexible piping systems can lead to incorrect estimates of the flow and structural parameters; these values should not be used for design.** Most seriously, their use can lead to poor estimates of the extreme parameter values, particularly pipe stresses. Fully-uncoupled methods are strictly applicable only to systems of high rigidity and should not be used to calculate fluid transients in flexible piping systems, except where fluid/structure interaction effects are likely to be small. An approximate means of assessing the importance of fluid/structure interaction is given in Section 3.2.

A further important advantage of computer programs using ***fully-coupled*** methods is their ease of use. The flow and structural parameters are solved together in a one-stage analysis, whereas the use of two separate programs is often required for a ***partially-*** or ***fully-uncoupled*** analysis.

Systems for which the effects of fluid/structure interaction should be investigated include high-pressure lines in processing plant (commonly suspended at discrete points from a supporting structure) and systems designed to have a degree of structural flexibility to allow for thermal expansion over the likely range of operating temperatures. Other applications are found in nuclear, petrochemical and power plants, and aircraft and rocket fuel systems. The program, ESDUpac A9331, is not applicable to continuously supported and damped piping systems such as buried water supply lines or oil pipelines.

Piping vibration due to external excitation (such as earthquake excitation or rotating machinery) and resonant vibrations in pulsating flow are not calculated by the program.

2.3 Applicability of Related ESDU Data Items

This Data Item is one of a group providing computer programs for the prediction of fluid/structure interaction in flexible piping systems. The applicability of the programs in the group to various types of piping system, defined by structural layout, is outlined in Table 2.2.

TABLE 2.2 Applicability of programs in the group on fluid/structure interaction

Piping configuration				Coupling type	Applicable programs
Layout	Arrangement	Bend types	Discrete pipe support types		
non-planar (3D) or planar (2D)	unbranched	fully-rigid, mass neglected	fully-rigid	fully-coupled	ESDUpac A9331
planar (2D)		fully-rigid or flexible, mass included	fully-rigid or flexible	partially-coupled	ESDUpacs A8822 and A8930

ESDU 88022 provides a computer program, ESDUpac A8822, for the calculation of the natural vibration parameters (natural frequencies, mode shapes and generalised masses and stiffnesses) of flexible planar pipelines with elastic or rigid supports and attached components. Graphical techniques are also provided for the estimation of some natural frequencies of simple piping configurations. The natural vibration parameters calculated by ESDUpac A8822 are required as input data to the computer program of ESDU 89030, which calculates the fluctuating values of the fluid and structural parameters. Although the combined use of these two programs restricts the user to the analysis of planar piping systems, it is possible to uncouple the flow and structural parameters. Further guidance on the features of ESDU 88022 and 89030 is given throughout this Item.

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A further group of Data Items is available for the estimation of transient pressure and flow changes within piping systems in which fluid-structure interaction effects are not included (that is, the pipework is assumed to be rigid). Transient pressure changes are generated by changes in operating conditions of components such as pumps and valves. The effects on the flow conditions of various surge suppression devices can be investigated. Data are provided for unbranched systems and networks. Time histories of fluctuating pressure and flow can be calculated using the computer programs of ESDU 84013, 85009, 85044, 86015 (for rapid transients in steam lines, and available as ESDUpac A8615) and 87027 (for liquid-filled networks, and available as ESDUpac A8727). These data can be used to estimate the time histories of fluctuating forces.

3. CRITERIA FOR COUPLED ANALYSIS

3.1 Coupling Mechanisms

In order to obtain reliable estimates of the liquid and structural parameters in non-rigid piping systems following a flow disturbance, it is necessary to use a model in which both sets of parameters are coupled. The three main coupling mechanisms are described below.

(i) **Junction Coupling**. This is a mechanism which acts locally at bends and other flow discontinuities (such as unrestrained valves). It is usually the most important coupling mechanism in industrial applications (such as pipelines in chemical processing or nuclear plant), and is usually much less important in long pipelines or in piping systems with few or no sharp bends, where Poisson coupling is likely to be more significant. Junction coupling accounts for the unbalanced fluctuating pressure forces at flow discontinuities, which are treated in the model as fluctuating point loads.

At steady-state conditions of uniform flow throughout the piping system, the forces at the junctions and flow discontinuities can lead to minor deflections from the unpressurised position of the pipework. During a transient event, the fluctuating pressure differences across the flow discontinuities can lead to structural motion which in turn affects the pressure and flow velocity.

(ii) **Poisson Coupling.** This is often much less important than junction coupling, especially in piping systems that are more flexible in bending than in the axial directions. Poisson coupling arises from the local interaction between the liquid pressure and the hoop stress and strain in the pipe wall. Local values of longitudinal strains, which are related to hoop strain by the local values of Poisson's ratio, lead to longitudinal stresses in the pipe walls that are reacted by the restraints and by the inertia of the system. These longitudinal stresses propagate along the pipework as axial stress waves (much more rapidly than the pressure waves in the liquid), which in turn leads to changes in the pressure and flow velocity due to the small, but often significant, changes in pipe flow area.

Poisson coupling is neglected by setting the values of Poisson’s ratio to zero in all members.

(iii) **Friction Coupling.** This form of coupling accounts for the frictional interaction between the pipe wall and the fluid, and is distributed along the pipes. Friction coupling is the least important form of coupling in that it has a small effect on the overall response.

All three coupling methods are included in the **fully-coupled** program of this Data Item. The methods of ESDUpac A8930 (see Section 2.3) are **partially-coupled**, in that junction coupling is included and Poisson and friction coupling are neglected.

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3.2 Criteria for Assessing Importance of Fluid-structure Interaction

The following approximate criteria can be used to assess the importance of fluid/structure interaction in the response of piping systems to changes in the internal flow conditions. The assessment requires the estimation of the following three time scale parameters.

(1) **Time scale for pressure waves in the liquid**, T_a. This parameter is the duration of a full cycle of transient pressure waves in the contained liquid, and is given as

$$T_a = 4\Sigma(L/a), \tag{3.1}$$

where the summation is performed over each member in the model. For models in which the wave speed, a, is common to all members (that is, where all members are of uniform section and material properties, see Section 5.2.2), this equation simplifies to $T_a = 4L/a$, where L is the total length of the system. Guidance on the estimation of wave speed, a, is given in Section 4.3.6.

(2) **Time scale for dominant mode of structural vibration**, T_ω. In many applications, the structural dynamics are dominated by only a few modes of vibration (and often by a single mode with the lowest natural frequency, referred to as the fundamental mode). In order to specify a value for T_ω, it is necessary to estimate or measure the natural frequencies of the piping system and identify the likely dominant modes. This time scale is given as

$$T_\omega = 1/f_j, \tag{3.2}$$

where f_j is the frequency of the highest of the identified dominant modes. If the dominant modes are translational, it is likely that junction coupling is the most significant mechanism. Similarly, a dominant axial mode is likely to indicate that Poisson coupling is significant. Further guidance on these mechanisms is given in Section 3.1. ESDU 88022 can be used to predict the modes of vibration of certain flexible piping systems (see Section 2.3).

(3) **Time scale for flow disturbance**, T_{fd}. This time scale accounts for the changes in the flow conditions that initiate fluid transients. For systems where transients are initiated by valve operation, the time scale T_{fd} is a measure of the time taken for the changes in the flow rate at the valve to occur. For total valve closure assuming a linear decrease in flow rate to zero it is equal to the valve closure time, t_c. However, such linear changes in flow conditions are unusual and it is recommended that T_{fd} is taken to be the period over which 90 per cent of the change in the flow rate at the valve occurs. A similar criterion applies in systems with pumps running-down (tripping). Further guidance on pump and valve modelling is given in Sections 4.4.2 and 4.4.3, respectively.

As a general guideline, it is likely that fluid/structure interaction is important in a fluid transients analysis if the following conditions are satisfied:

$$T_\omega < T_a, \tag{3.3}$$

and

$$T_{fd} < T_a. \tag{3.4}$$

These inequalities are, respectively, measures of the flexibility of the system and of the speed of change of flow conditions (relative to the time scale for a full cycle of transient pressure waves).

These guidelines are based on a similar method presented in Reference 10.

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3.3 Selecting Run Time (Flow Period), *T*

In order for an analysis to account reliably for the pressure and flow fluctuations and the dynamic behaviour of the piping system, the run time, T, should satisfy the following criteria, which are based on the three time scales defined in Section 3.2.

(1) $T > T_a$, where T_a is the time scale for the pressure waves in the liquid.

(2) $T > T_\omega$, where T_ω is the time scale for the dominant mode of structural vibration.

(3) $T > T_{fd}$, where T_{fd}, is the time scale for the flow disturbance.

The run time should be long enough to ensure that extreme values of the parameters have been calculated (a requirement usually satisfied by the arbitrary relationship $T > 4T_a$).

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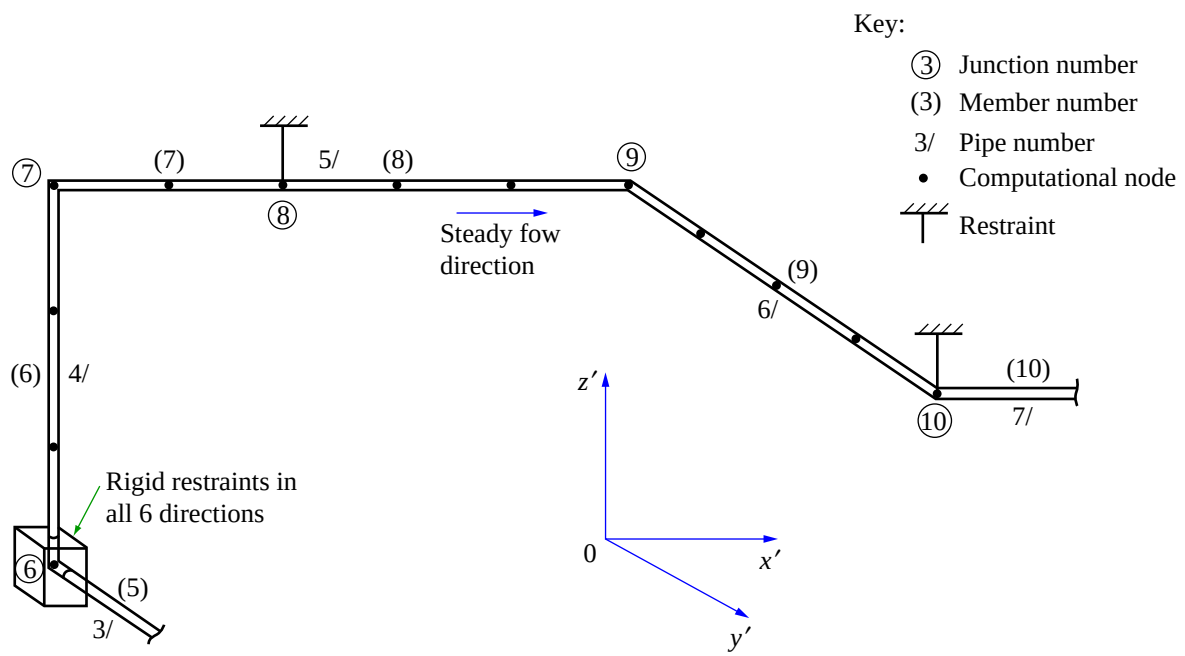
4. PIPEWORK MODEL

This section provides guidance on the idealised model of the piping system used by the computer program. Definitions of the terminology applied to the parameters of the model, and a glossary of terms, are given in Section 4.1, and the model is outlined in Section 4.2. Guidance on the estimation of parameters relating to the pipework structure and of the liquid parameters is given in Section 4.3. Guidance on the modelling of upstream and downstream components is given in Section 4.4. Model segmentation is discussed in Section 4.5, and the method of solution for the model is outlined in Section 4.6. The validation of the program is discussed in Section 4.7.

4.1 Definitions of Model Parameters and Glossary of Terms

A simple piping system is shown in Sketch 4.1. The model is assumed to consist of a number of **members**, or straight lengths of pipe, connected at **junctions**. Each junction is referred to as a **boundary condition**, and at each end of the piping system there is a **component**. The component at the upstream end is either a pump or a constant pressure point (reservoir). Similarly, the downstream component is either a valve or a constant pressure point. The option is provided to model rigid restraints in any of the three translational and three rotational degrees of freedom of each junction.

For the purposes of the computer model each member is divided into a number of **segments** and the instantaneous values of the fluctuating flow and structural parameters are calculated at the ends of each of these segments, or **nodes**, at each **time step** over the **flow period** of the analysis.



Sketch 4.1 Simple piping system used to illustrate model parameters

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Glossary of terms

The following terms are used throughout and are defined here for convenience.

Boundary condition	Either a **component** (at the upstream and downstream ends of the piping system) or a **junction** (elsewhere in the piping system).
Component	At the upstream end of the piping system, either a pump or a constant pressure point. At the downstream end, either a valve or a constant pressure point. See Sections 4.4.1, 4.4.2 and 4.4.3.
Degrees of freedom	There are six degrees of freedom at each **junction**, three translational (in the orthogonal x'-, y'- and z'-directions) and three rotational (about x'-, y'- and z'-axes).
Junction	A connection of two pipes or a change in cross section or the location of one or more **restraints** or the ends of the piping system (that is, the **boundary conditions**).
Member	A straight length of pipe of uniform section and isotropic material properties (see Section 4.2).
Node	Refers to the ends of **segments**. Instantaneous values of the flow conditions and structural parameters are calculated at each node at the end of each **time step**.
Run time (flow period)	Time interval over which the fluctuating conditions are simulated. Guidance on the choice of a suitable flow period for a particular analysis is given in Section 3.3.
Segment	Each member in the model is subdivided into a number of **segments** of equal length. Guidance on the division of the **members** into segments is given in Section 4.5. See **node**.
Support	A rigid restraint preventing translational or rotational deflection.
Time step	A requirement of the computer model which calculates fluctuating flow and structural parameter values at a number of discrete time intervals over a specified **flow period**. See Section 4.5 for further guidance on this parameter.

4.2 Idealisation for Pipework Model

ESDUpac A9331 is based on idealised models of real piping systems. Sketches 2.1 and 4.2 show typical systems of the type that can be modelled by the program. The following idealisations are made for the computer model.

(i) Each member of the piping system is of circular, uniform cross-section and is assumed to lie parallel to one of the three orthogonal directions x', y' and z'. Isotropic material properties are also assumed over its length.

(ii) The steady flow velocity is assumed to be very small compared to the wave speed in the liquid (typically less than 10 per cent).

(iii) All bends and end connections are assumed to be fully rigid, with all flexibility of the piping system arising from the elasticity of the straight length of pipe in bending, shear, torsion and by axial deformation (that is, all bends are assumed to remain at 90°). As a rough guide, bend flexibility

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