# FROUDE MODELING OF THE FLIXBOROUGH "BY-PASS" PIPE

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The Flixborough works in the United Kingdom was destroyed by a powerful explosion twenty-five years ago (June 1, 1974). The cause of the explosion was determined to be the failure of a temporary pipe bridge (the 'dog-leg' pipe), installed between two reactors. The failure mechanism of the dog-leg pipe has been the subject of extensive research and controversy. To date, no failure mechanism, that did not require excessive over pressure, has been accepted. The flow in a one-sixth scale model of the 'dog-leg' 'by-pass' pipe assembly of the Flixborough chemical plant is examined using Strouhal and Froude number analyses, as well as laser Doppler velocimeter (LDV), video and proximeter displacement transducer measurements. The work investigates the one possibility that appears to have received little consideration - that of a partial circumferential fatigue crack in one of the bellows supporting the ends of the pipe caused by flow induced vibration. In this analysis, the approximate axial, lateral and angular (rocking) natural frequencies of the pipe and bellows assembly were determined. These, scaled to the one-sixth flow model used, were compared to flow frequencies measured by video analysis, LDV, and proximeter displacement measurements as well as those determined from Strouhal and Froude number analyses of the possible flows past the bellows.

The results indicate that both axial and lateral near resonance conditions of the bellows and the structure could have occurred. Such conditions may have been responsible for a fatigue initiated two-step failure process that is better supported by the physical facts and eyewitness accounts and does not require the over pressure necessary for the single step simultaneous failure of both bellows accepted, albeit reluctantly, by the Court of Inquiry.

Keywords: Flixborough, LDV, fluid structure interaction, flow induced vibration

## INTRODUCTION

On June 1, 1974 there was a fire and explosion at the Nypro (UK) Ltd. works near Flixborough, North Lincolnshire. An accidental release of Cyclohexane at 8.6 barg. and between 150 to 155 ºC resulted in an unconfined vapour cloud explosion which caused 28 fatalities and the destruction of the plant as well as severe damage to many buildings in the surrounding countryside.

The catastrophe was initiated in section 25A of the process stream during start-up while Cyclohexane feedstock, inerted with nitrogen, was under hot recycle, through the reactor train, R1-R6. In the oxidation sequence the fifth reactor, R5, had been removed and a temporary 0.5 m diameter pipe-bridge, which used the two original 0.7 m diameter bellows and stub pipe assemblies, had been installed between R4 and R6.

The reactors were fitted with interior overflow weirs and interior baffle plates to ensure level control and bottom feed, proper oxidation and mixing times respectively (Figure 1).

The original interconnecting pipes and their bellows had permitted the hot pressurized feedstock to communicate by open channel flow over the outlet weir in the upstream reactors, through the bellows connections, into the downstream reactors with a fixed difference in elevation of 0.178 m. This adaptation, however, doubled the head to 0.356 m and additionally resulted in two hydraulic jumps in the very complex flow structure observed (Figure 2).

The plant had operated for two months, nearly continuously, since the modification and before the explosion.

An official Court of Inquiry was appointed to hold a formal investigation so "to establish the causes and circumstances of the disaster and to point out any lessons . . . . to be learned therefrom" (Dept. Of Employment 1975). The essential problem faced by the Court was "to determine what had caused the rupture of the by-pass."

The possibilities investigated were: "i) rupture of the by-pass assembly through internal pressure; ii) rupture of the assembly in two stages; a small tear in the (*upstream, i.e., R4*) bellows leading to an escape and a minor (*but external)* explosion causing final rupture; and iii) rupture of the '8 inch' line at the 50-inch split leading also to a minor explosion causing rupture of the by-pass assembly".

Processes ii) and iii), as stated, specified an external minor explosion to trigger events; no physical evidence of this was determined thus effectively limiting the possibilities to a consideration of i) only. Despite physical evidence of an internal, and perhaps prior, tear in bellows B4 (i.e., process ii)) and compelling eyewitness evidence only three paragraphs in the final report were devoted to the consideration of the two-stage rupture possibility ii).

On the basis of expert evidence by Newland (1976), based on a dynamic analysis and assessment of energy requirements for both bellows to squirm and the by-pass pipe to buckle as one event, the Court concluded, albeit with low probability, "that the disaster resulted from a one stage failure of the 20-inch assembly" . . . as a result "of conditions of pressure and temperature more severe than any which had previously prevailed but no higher than careful and conscientious plant operators could be expected to permit." The Court did however state that this conclusion "would be readily displaced if some (*other event of*) greater probability to account for the rupture could be found".

Extensive full scale experiments, which did not involve flow, however, were undertaken in attempts to duplicate the failure. These employed a similar pipe assembly as well as other bellows tests evaluated at the same and more severe operating conditions. These experiments were unable to reproduce the failure process accepted by the Court.

In view of its hesitant conclusion the cause of the accident has been the subject of considerable controversy especially as to the actual failure process, the amount of Cyclohexane released, and whether the UVCE formed from its release detonated (Gugan (1978), Phillips (1981).

In this paper we examine the flow conditions prevailing in the pipe and perhaps necessary for the failure to have been initiated by fatigue. In this case it is shown possible that flow induced vibration could cause a crack (know to have been formed in the R4 bellows) to initiate a release scenario that is perhaps more probable than that accepted by the Court.

The mechanism proposed requires first a significant tear in the upstream, B4, bellows. This would be followed by a local vapour-gas depressurization and the subsequent boil-up of the now superheated and supersaturated Cyclohexane (Cyclohexane's vapour pressure is only 0.51 MPa at the operating temperature). The impact of this rapidly swelling two-phase fluid would result in a head-space impact and dynamic over pressurisation (Gromles (1984), Venart and Ramier (1998)) immediately causing both the compression of the downstream, B6, bellows **and** the upwards 'squirm ' of the B4 bellows (Venart (1999), Venart and Tan (2000)).

The compression of B6, by this local over pressure, constrains the dog-leg pipe at its R6 connection and causes the process of B4 squirm to act over the full 356 mm eccentricity. This results in the collapse, by buckling, of the 0.5 m pipe as the B4 bellows bursts at its normal operating pressure. This failure process allows for twice the eccentricity accepted by the Court; and therefore only requires normal operating pressure (Venart and Tan (2000)).

The p-V work of the expanding two-phase Cyclohexane in the B4 bellows, and the constraint of the compressed B6 bellows, results in the formation of a pinched and collapsed

 

0.5 m pipe at its lower miter bend; the B6 bellows can still, however, be intact at this point though some discharge could occur through the 0.5 m pipe "pinch" at the buckled lower miter joint.

Because of this sequence of events only one exit, the R4 outlet, is available initially to release up to 370 kg/s of Cyclohexane for some 30 s. This discharge of some 10 tonnes (Venart (1999)) is much less than the 30-60 tonne estimates previously estimated (Sadee *et al* (1976/1977), Roberts and Pritchard (1982)).

The paper examines the flow within the by-pass pipe assembly using a one-sixth scale model of the pipe and its connections. LDV, video and proximeter displacement measurements are combined with estimates of the natural frequencies of the bellows supported assembly to suggest that the crack found in a piece of the upstream, R4, bellows (Folley (1974) may have been formed due to fatigue caused by flow induced vibration (Weaver and Ainsworth (1989)).

## THE 'DOG-LEG' PIPE ASSEMBLY

The design of the 'dog-leg' pipe was certainly inadequate. According to the Court, calculations were only made to determine if the pipe was large enough to carry the required flow and safely contain the pressure. The pressure capability of the assembly, as an eccentrically and internally loaded vessel, was not assessed, nor were the effects of the changed flow and its influence on the spring-mass system created by the bellows, pipe and fluid; in fact these latter concerns were hardly addressed in the proceedings.

### The bellows

The two bellows had a mean diameter of 749 mm and were about 230 mm long with 12 convolutions. They were constructed by a cold rolling process from sheet 316L stainless steel originally about 1.2 mm thick; the process of forming reduced the material thickness to about 1 mm. As formed, each unit had axial, lateral and angular stiffness in the range of 2770-3300, and 43208-51475 lbf/in as well as 5226-6225 lbf-in/deg (Warner 1975). Each bellows was welded to 304L stainless steel stub pipes, which in turn were bolted up to heavy flanged connections with the reactors and the 'dog-leg' pipe. The natural axial frequency of the bellows was about 65 Hz.

### The dog-leg pipe

This dog-leg pipe was fabricated from 304L stainless steel pipe 508 mm in diameter some 4.8 mm thick with two miter bends and was 3.91 m long between bellows (Figure 3).

The complete empty assembly, including the stub pipes with their flanges and bolts, weighed just over one tonne (1,112 kg). Interior fluid mass, taking into account fluid distribution due to flow, increased the total weight to over one and one half tonnes (1625 kg). The assembly was supported, while cold, with spans of standard scaffolding; with the thermal expansion of the reactors to operating conditions, support to the assembly was lost. The natural frequency for such a spring-mass system was in the range of 3-5 Hz axial, 13-16 Hz transverse and 25-30 Hz for the rocking mode and so fluid-structure excitation, particularly in the axial direction, became a possibility.

## EXPERIMENTAL FACILITY

The flow in the dog-leg pipe assembly was determined using a one sixth scale model and Froude number scaling. LDV, video and proximeter measurements and analysis were utilized.

**Froude number scaling**

When a flow is governed by inertia and gravity forces, such as in open-channel flow, the applicable dimensionless parameter used to characterize the flow is the Froude number. This is expressed as the ratio of the inertia to gravity forces. Of course in all flows there will be other forces acting such that there is more often more than one characteristic number that can be utilized to characterize it, *e.g.* the Reynolds and Strouhal numbers. The conditions necessary to satisfy any two parameters are, however, usually conflicting or require the use of unattainable modeling fluids. The accepted experimental approach is to select the dominant number(s), in this case the Froude and Strouhal numbers. Although the conditions for say the Reynolds are violated, provided the flow is turbulent, reliable experimental results may still be obtained from the model, Bakhmeteeff *et al* 1982.

Table 1 illustrates the Froude number model scales employed for the one-sixth model employed. Table 2 shows the calculated dynamic characteristics of the model and prototype.

**Table 1. Froude number model scales**

| Characteristic (Symbol) | Froude Scaling | | Comments |
|---|---|---|---|
| | Term | Ratio | |
| Length (L) | $L_r$ | 0.167 | - |
| Time (T) | $L_r^{0.5}$ | 0.409 | - |
| Velocity (V) | $L_r^{0.5}$ | 0.409 | - |
| Density (ρ) | $\rho_r$ | 1.55 | - |
| Mass (m) | $L_r^3\rho_r$ | 7.21 x $10^{-3}$ | - |
| Frequency (f) | $L_r^{-0.5}$ | 2.45 | - |
| Discharge (vol/sec) (Q) | $L_r^{2.5}$ | 0.011 | exp. ratio: 0.014 |
| Kinematic viscosity (ν) | $L_r^{1.5}$ | 0.068 | exp. ratio: 3.04 |
| Force (F) | $L_r^3\rho_r$ | 7.21 x $10^{-3}$ | - |
| Pressure (P) | $L_r\rho_r$ | 0.258 | - |

**Table 2. Dynamic characteristics of model and prototype**

| Parameter (Symbol) | Prototype | Model | Scale Ratio (M/P) |
|---|---|---|---|
| Velocity (V) (m/s) | 8.3 | 3.8 | 0.458 |
| Froude number ($F_r$) | 12.45 | 12.26 | 1 : 1 |
| Reynolds number (Re) | 1.1 x $10^6$ | 3.7 x $10^4$ | 1 : 31 |

**The model**

The scale model of the by-pass assembly and its connections was fabricated in acrylic. The model consisted of two open rectangular channels, representing the up and down-stream reactors, connected together by the model dog-leg pipe. The pipe was connected to the stub-pipes of the channels by surgical rubber cuffs, representing the bellows, and suspended from a bracket arrangement. The three sections of the apparatus are shown in Figure 3.

The components all formed part of a closed loop hydraulic system through which water was circulated by means of a centrifugal pump.

The inlet channel (R4) consisted of a rectangular open-top chamber constructed to represent reactor No.4. The size of this chamber was 500 mm long x 250 mm wide x 400 mm deep. The discharge of the circulating pump was led into a honey-comb screen installed in the inlet channel. The honey-comb screen was installed to promote a uniform and reasonably still inlet flow conditions into the overflow baffle and then into the dog-leg pipe.
The experimental objective was to make LDV measurements in the dog-leg pipe section. The pipe was fabricated from three sections of tube, 4 mm wall thickness. The inside diameter of the acrylic pipe was 83 mm. The three sections were glued together to form two mitered joints. The slope of the inclined section of the pipe was about $21.5^{o}$ with the centre line of the horizontal section.

This pipe was installed between the inlet and outlet channels at each end by means of the elastic couplings. These elastic bands were clamped to the pipe and the stub pipe on each end. The couplings were used to represent the bellows in the prototype system.

The outlet channel was physically similar to the inlet channel except that the height of the former was about 70 mm less than that of the latter. The dimensions of the downstream channel were 500 mm long x 250 mm wide x 320 mm deep. A full-span rectangular weir was used to set the flow height in the chamber and also used to determine its discharge.

Tap water was used to model the process fluid. The physical properties of water and Cyclohexane are compared in Table 3. The mean temperature of the water was $20^{o}C$ ( room temperature).

**LDV system**

The unit used was a Dantec two-component, four beam, 4 watt argon-ion laser system. The instrument was operated in back scatter mode. The data size varied from 3000 to 4000 samples at each measurement point.

A dedicated computer was used for data manipulation and analysis. Special data manipulation software (Dantec SRE LDA2D version 3.0a) was utilized. The software determined the ensemble mean velocity from the time history of the particles activities. The local mean flow velocity and other flow velocity statistics such as the standard deviations were also computed.

The number of data samples used generally varied from one measurement location to another. Each sample size, however, was large enough to give reliable statistics to describe the flow. At the same time, the size of the sample was small enough to reduce the LDV data acquisition time. Between 3000 and 4000 samples were taken at each measurement point. The sampling time was manually determined with a stop-watch, as the system did not have the necessary hardware to measure these times.

**Pipe displacement measuring device**

In order to determine the fluid structure interaction a displacement type Proximitor (Brently Nevada Proximitor, 7200 series) was installed at two locations, at one point to determine axial displacements, the other location to record transverse movement in the vertical plane.

Full details of the model, its instrumentation and operation are given in Teng-yang (1997).

**Table 3 Dynamic and flow properties of the model and prototype**.

| Parameter (Symbol) | Prototype (Cyclohexane) | Model (Water) | Scale Ratio (M/P) |
|---|---|---|---|
| Density (ρ) ($kg/m^3$) | 645 | 998 | 1.55 |
| Kinematic viscosity (ν) ($m^2/s$) x $10^7$ | 3.306 | 10.05 | 3.04 |
| Discharge (Q) ($m^3/s$) x $10^3$ | 108 | 1.53 | 0.014 |

## MEASUREMENTS

The measurement sections are shown in Figure 4. To obtain representative velocity distributions along the assembly the measurement planes were located at or close to the following sections/components: elastic couplings (B4 and B6), sudden contraction and enlargements, and the mitered joints. A total of thirty-three measurements locations were investigated since at each location LDV measurements were made at three elevations in the flow; one near the surface, another near the bottom of the channel and the third at a point midway between the other two.

Three flow cases were examined, one for the scaled prototype full flow, another for flows greater and smaller than the scaled design flow. The discharge at design conditions was estimated to be 1.53 l/s of water corresponding to 108 l/s of Cyclohexane at about 150 ºC and 0.96 MPa.

The bellows were simulated by elastic rubber cuffs that did not scale in stiffness to those on the prototype. To a first order approximation, however, the pipe could be considered to oscillate, in the axial direction, freely and its natural frequency determined. The natural axial and transverse frequencies of the pipe assembly, as estimated from the proximiter displacement waveforms obtained with the pipe empty, were 5 and 7 Hz respectively.

### Qualitative description of the flow

The flow from the Inlet chamber passes over the overflow baffle in the form of a ‘waterfall’ into the entrance region of the pipe. Here the flow accelerates and plunges into the pool formed at its base. The flow then travels past the upstream stub pipe and its adjacent junction piece between the pipe bridge into Plane 3 (Figure 4). The reduction in pipe diameter at this section results in a flow restriction, level increase and fluctuations of the free surface of the flow. Beyond this point within the now smaller diameter pipe there is flow acceleration as it approaches the upstream miter joint, where it attains its greatest velocity, with little variation in its free surface. A hydraulic jump is next formed at the base of the incline at the lower miter joint. This jump is characterized by a rise in the depth of flow, and significant oscillations, both axial and vertically, in the flow. Downstream of the jump, the flow decelerates and fills the pipe flowing into the lower stub end pipe into the outlet reservoir. Like its upstream counterpart, this end of the pipe was observed to oscillate both axially and laterally with the flow.

The entrance region of the pipe (P1) was located about 57 mm below overflow baffle. Here, very high recirculation and mixing was observed. The rapid mixing was characterized by both axial and transverse oscillations in the flow, the effect of which appeared to cause the pipe to oscillate.

Vertical flow fluctuations were also evident at the change of section after the simulated bellows. The fluctuations in the free surface at this location (plane 3) was determined from the video analysis to be about 12 to 14% of a pipe diameter, relative to the larger pipe of 114 mm diameter. The frequency of these vertical oscillations was about 3.75 Hz. as determined from frame by frame video analysis.

Beyond plane 3, the flow accelerates from a subcritical to supercritical state as it enters the inclined section. Under the design conditions, the pipe here was flowing about half full. This flow next plunges into the lower section of the pipe after the lower miter bend, decelerates and forms a hydraulic jump. The fluctuations of the free surface that accompanied the jump were estimated (again from video analysis) to be between 35 and 65 percent pipe diameters based upon the smaller pipe diameter. The frequency of oscillation was estimated to range from 2.7 to 6.0 Hz in the vertical direction and 3.0 to 3.8 Hz in the axial direction..

Although the pipe flowed full downstream of the jump most of the time, occasionally a “long” bubble was observed to form. This bubble was observed to axially slug and oscillate in the pipe as it proceeded to the outlet chamber. The interaction of these fluctuations with the pipe resulted in considerable pipe oscillation due to fluid-structure interaction.

**Velocity measurements**

The raw flow velocity data obtained from the LDV measurements were stored on disk. Due to hardware limitations, the system could not measure the exact sampling time intervals between Doppler bursts. Since this information was needed to estimate the frequency response of the instrument, it was estimated by measuring the total time for data collection at a measuring point using a stop watch and dividing this time by the number of samples obtained. A uniform temporal sample rate was thus assumed.

**Velocity statistics**

The detailed measurements and the statistics of the measurements for all the flow cases investigated are to be found in Teng-yang (1997). The statistics were determined by the LDV data analysis unit from the probability distribution functions (pdf) of the sample data. The summary results use the four statistical measures of the measurement: the mean, standard deviation, skewness and kurtosis. Turbulent intensities were estimated by dividing the velocity fluctuation (rms values) by the corresponding mean velocity at a given point..

The mean velocity from the summary results are plotted in Figure 5. In this figure, the velocity is plotted as a function of the measurement plane. The three bars represent the velocity measurements at the first, second and third measurement points for the respective plane. The dashed lines represent the arithmetic average of the mean velocities. These lines approximately define the envelope of the velocities at the measurement points. In some cases only restricted numbers of measurement planes could be accessed. No measurements were made at P11.

Figure 6 indicates the root mean square (rms) values.

**Pipe displacements**

Information about the frequency constituents of the pipe displacements were also obtained from analysis of the raw proximiter data. This information was obtained by processing the raw data in VU-POINT (1992). The data was imported into VU-POINT and fast Fourier transformed (FFT).

The dominant frequency components, obtained by the fast Fourier analysis, represent the induced excitations imposed on the pipe assembly by the flow; these are indicated in Table 4 for the design flow case only. It can be seen that significant amplitude deflections occur in both the axial and lateral vibrational modes for the pipe at 2.4, 5.4 and 7.3 Hz. These values correspond to prototype frequencies of 1, 2.2 and 3 Hz and are thus close to some of the natural frequencies of the assembly.

 

## DISCUSSION

The measurement data was presented in the preceding section.. Here, the data are analyzed and discussed. First a discussion of the velocity data will point out how these may be used in an examination of the fatigue life of the prototype bellows. The results of the frequency analysis are also discussed in order to identify possible resonance frequencies.

### Velocity data

Since the summary data are similar for all the three flow cases considered, we shall limit our analysis to the design flow condition. The velocity measurements for this case, are illustrated in Figures 5 and 6. For convenience the measurement planes are divided into three sections: Sections 1 to 3. Section 1 consists of Planes 1 to 3, Section 2: from Planes 4 to 9, and Section 3 of Planes 10 and 11.

The measurements indicate subcritical flow in Section 1; the maximum mean velocity measured there was about 0.49 m/s for the model, about 0.1 m/s less than the critical velocity of 0.59 m/s. The flow turned supercritical in Section 2, where the velocity was 0.90 m/s; the maximum in the measurements (Plane 6). The range of the mean velocities at Plane 4 was between 0.50 and 0.63 m/s, which suggests critical conditions around this location. The flow turned subcritical again in Section 3 after the hydraulic jump. The lowest velocity measured in this section was about 0.28 m/s. The mean velocity distribution for Case 1 is graphically depicted in Figure 5.

The distribution of the velocity is reflected in the velocity fluctuation (rms values) plot (Figure 6). Comparing Figures 5 and 6, it can be seen that the 'peaks' and "valleys" of one are reversed on the other. Physically, this means that in the subcritical regions of the flow, velocity fluctuations are large. In contrast, the high velocity region (Planes 4 to 6) is characterized by low velocity fluctuations. Thus, in the subcritical regions of the flow (Sections 1 and 3), relatively high velocity fluctuations (about 0.11 to 0.17 m/s about the mean velocity) were observed. On the other hand, the velocity fluctuations in the supercritical region (Section 2) were between 0.06 and 0.07 m/s of the mean velocity.

**Table 4 Frequency components of pipe displacement, design flow**

| **Flow Configuration** | **Axial** | | **Lateral** | |
|---|---|---|---|---|
| | **Freq. (Hz)** | **Amp. (mm)** | **Freq. (Hz)** | **Amp. (mm)** |
| Design Flow (1.53 liter/s) | 2.4 | 0.243 | 2.4 | 1.34 |
| | 5.4 | 0.31 | 5.4 | 1.15 |
| | 7.3 | 1.16 | 18.1 | 0.251 |
| | 10.3 | 0.603 | 21 | 0.171 |
| | 17.6 | 0.209 | - | - |
| | 35.2 | 0.241 | - | - |

 

**Discussion**

The analysis of the mean velocity and velocity fluctuations are consistent with the visual observations made during the measurements. Based on the analysis of the flow presented above, a possible origin of the excitation force may be attributed to velocity fluctuations in the flow.

The type of distribution of the data can be inferred from values of the skewness and kurtosis obtained from the velocity measurements. The kurtosis profiles generally indicated an average kurtosis of about three. This implies that, for most of the measurements, the velocity distribution was approximately normal. The tendency of the velocities towards a normal distribution profile was correlated fairly well by the skewness values.

Assuming a confidence limit of 95 percent (two standard deviations), the maximum the velocity fluctuation would be about ± 0.84 m/s about the mean velocity at location 2 on measurement plane 1. The fluctuating pressure corresponding to this velocity was estimated from equation (1.1) to be about 1.4 kPa for the prototype. The fluctuating stresses associated with this pressure fluctuation on the bellows were also determined. The stress range due to the pressure would have been about 1.3 MPa for the meridional membrane stress, and about 1.2 MPa for the meridional bending stress.

Other factors can also contribute to pipe oscillation. Oscillations can be amplified by flow level variations generated by the drop at the entrance region of the pipe. The entrance region of this pipe was located at the base of the overflow baffle in the inlet chamber, only 0.46 pipe diameters downstream of the bellows.

The base of drops are characterized by high flow oscillations. Energy losses associated with drops have been experimentally investigated by Rajaratnam and Chamani (1995). They found that the loss at a drop was mainly due to intense mixing of the jet with the pool behind it. In the mixing zone, the flow was found to be highly fluctuating, with flow recirculation. An important observation by them was that the falling jet oscillated with the degree of oscillation being dependent on the ratio of the drop height to the critical depth of the flow approaching flow. They found this frequency be 7.5 Hz, for a critical depth to drop height ratio of between 0.06 to 0.35. For our experimental model, this ratio was determined to be about 0.13, well within the range of the ratios considered. Consequently, we can expect flow oscillations in the neighborhood of 7.5 Hz at Plane 1 due to the drop . The effect of this induced frequency can only be to accentuate the pipe oscillations since it is close to the natural axial frequency of the assembly. The hydraulic jump formed at the foot of the incline pipe section could also act as another source of excitation for the pipe. The formation of the jump is accompanied by high turbulence and large flow oscillations. The frequency of these features was determined from video analysis to be in the range 2.73 to 6.0 Hz in the vertical direction, and 3.0 to 3.75 Hz in the transverse direction. This frequency range was significant in contributing to pipe movement. The effect of change of the pipe section was similar to the hydraulic jump. The continuous impact of the water on the annulus between the large and small pipes, due to this fluctuating water level, induced further pipe oscillation.

**Analysis of the Flow-induced Oscillations**

A substantial fraction of the flow variation occurs at the low end of the frequency spectrum. The power spectrum exhibits a decline with high frequencies. These local peaks are visible at 1.6, 5.7, and 6.8 Hz respectively.

Frequency analysis of the pipe displacement indicated that greater energies were associated with oscillations, also at the low region of the frequency spectrum This region of high energy components was located approximately between 0 and 25 Hz with most of the energy concentrated at frequencies about 2.5, 7.5, and 10 Hz.

The natural frequencies of the model pipe assembly were measured in this experiment. The axial and lateral frequencies were found to be about 5 and 7 Hz respectively. The fact that these frequencies are low indicates these modes are excitable by the flow whose fluctuating frequency is also low.

The natural frequencies of the full-scale dog-leg assembly were estimated to be between 3-5, 16, and 28 Hz for the axial, lateral, and rocking frequencies. These calculated frequencies are based on a very much simplified model of the dog-leg pipe in which it was replaced by a single section of equal weigh. For this reason, the calculated natural frequencies should be considered only as a guide to the order of values expected.

The flow frequencies identified above can be scaled to the full-size dog-leg pipe assembly. The full-scale excitation frequencies corresponding to the observed local peaks in the model test are approximately 0.6, 2.3, and 2.8 Hz. These are sufficiently close to the estimated natural frequencies of the dog-leg pipe assembly to suggest that flow induced vibration of the assembly may have been significant. Self excitation of the bellows is also possible (Weaver and Ainsworth (1989)) as the Strouhal Number, based upon skewed flows, such as occur at the base of the weir overflow, is 0.54. It is significant that well over 10 million cycles of the bellows could have occurred just due to the start-up flow alone; based upon the lower frequency vibration of the assembly in excess of several hundred million cycles were possible. It is well known that under random vibration conditions (Crandall (1963)) that the absolute magnitude of the amplitude follows a Rayleigh distribution so that there will be ***no*** fatigue limit (Au-Young (1999), Miller (1999)).

## CONCLUSION

In this work, a one-sixth scale model was used to study the flow in the Flixborough dog-leg pipe assembly. The flow model was based on Froude number scaling, using water as the test fluid. LDV measurements of the streamwise flow velocities were made at key locations along the pipe. The velocity and velocity fluctuations were determined from the statistical measures of the flow. The nature of the velocity distribution of the flow was examined from plots of the measured velocity data.

Proximitor measurements of the displacement of the pipe were also made to determine the frequency of the system with flow in the pipe. Significant frequencies of the proximitor data were compared with determined natural frequencies (axial, lateral, and angular) of the bellows scaled for the model. A comparison was made to determine if any of the system frequencies (with flow) was close to the natural frequency of the bellows to create resonance conditions.

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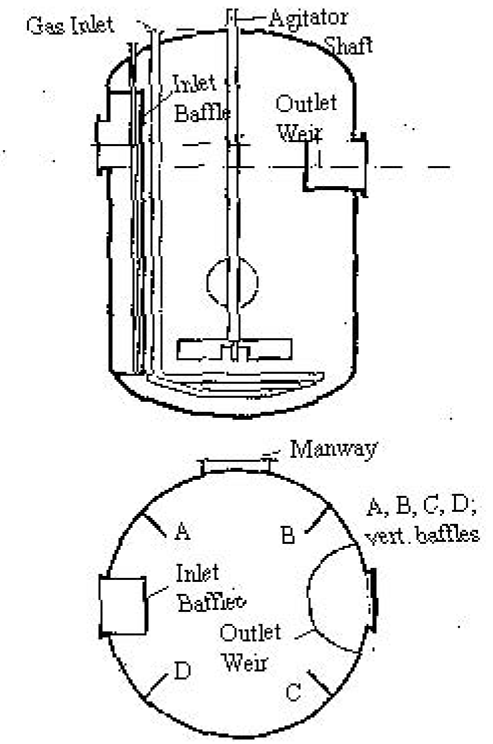


Figure 1. Reactor details (Artingstall 1974).

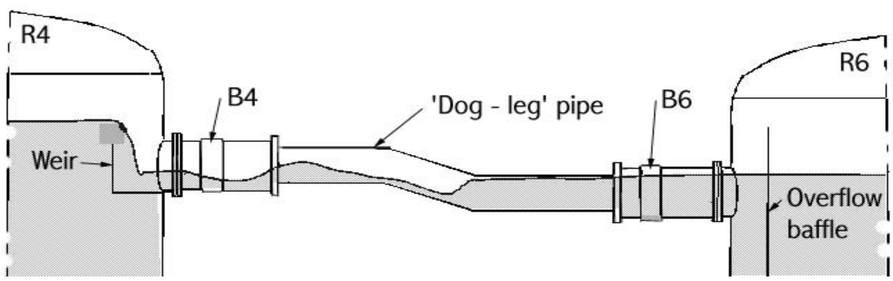


Figure 2. Reactor train, vessels R4-R6, showing temporary by-pass pipe and flow.

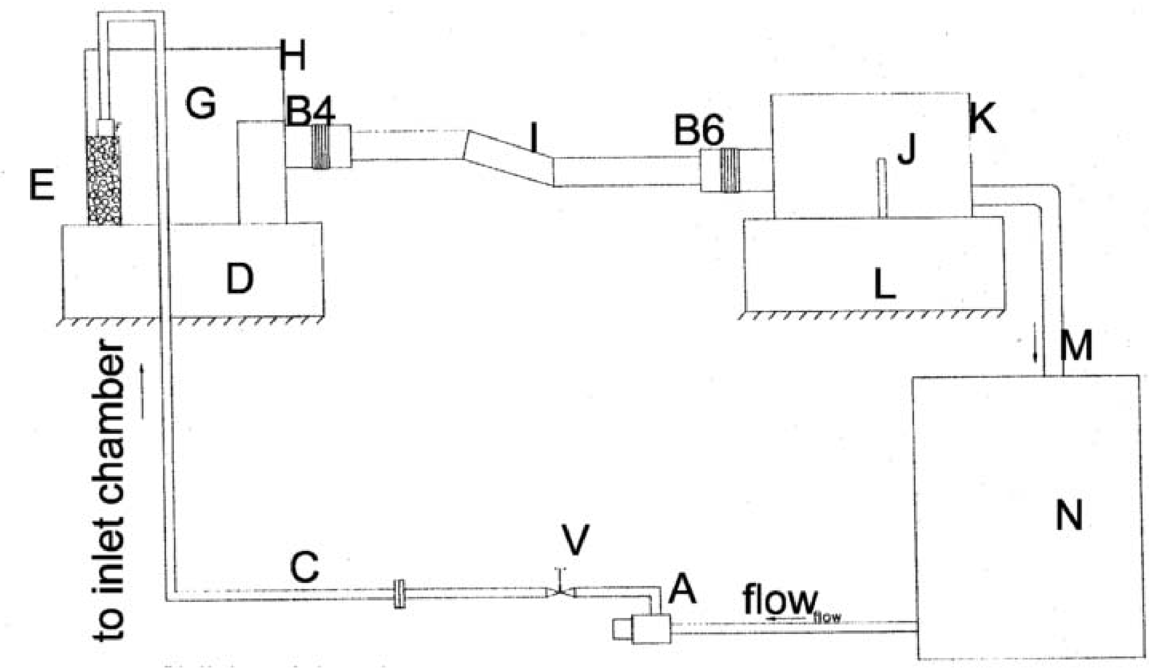


Figure 3. Flixborough ‘by-pass’ flow circuit.

Key:

A: Circulating pump
B4: Upstream elastic coupling
B6: Downstream elastic coupling
V: Pump discharge valve
G: Copper tubing (32 mm diam)
D: Inlet chamber support
E: Honeycomb screen
F: Flexible hose
G: Overflow baffle
H: Inlet chamber
I: Dog-leg pipe
J: Rectangular weir (full-span)
K: Outlet chamber
L: Outlet chamber support
M: Outflow pipe (PVC)
N: Reservoir

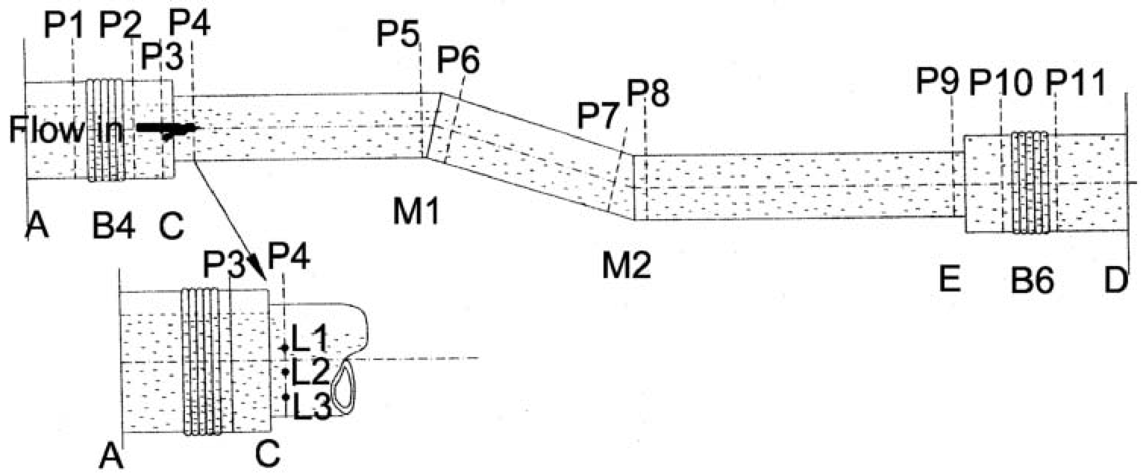


Figure 4. LDV measurement stations.

Key:
B4: Upstream elastic coupling
B6: Downstream elastic coupling
C: Section of sudden contraction
E: Section of sudden enlargement
M1: Upstream mitered joint
M2: Downstream mitered joint
L1, L2, L3: LDV measurement location Nos. 1, 2 and 3
P1 … P11: LDV measurement plane Nos. 1 to 11
Test liquid: Water

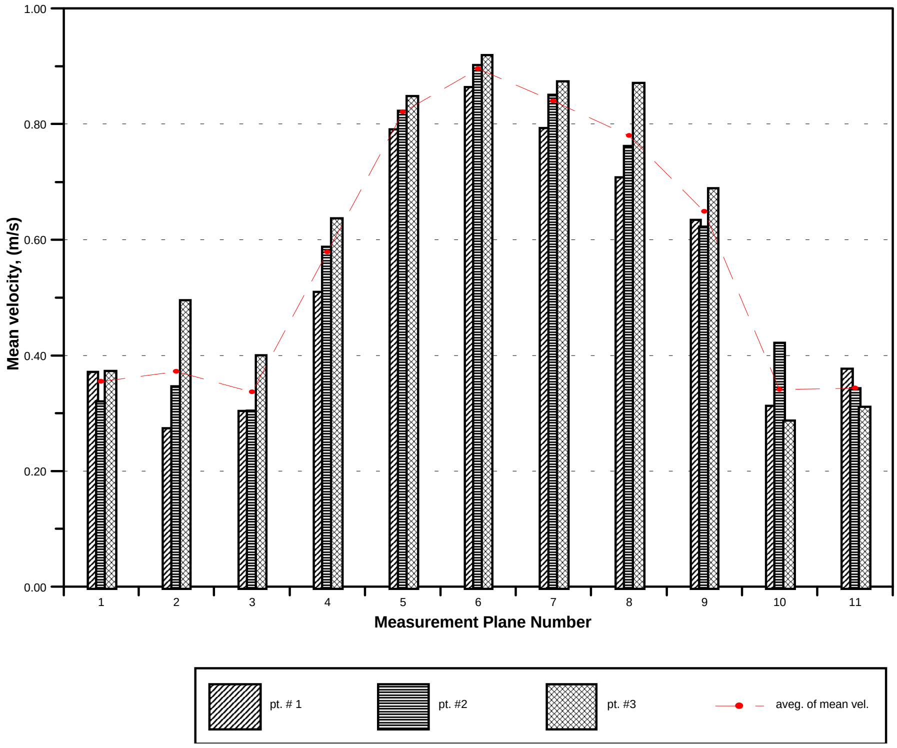


Figure 5. Mean velocity, design flow.

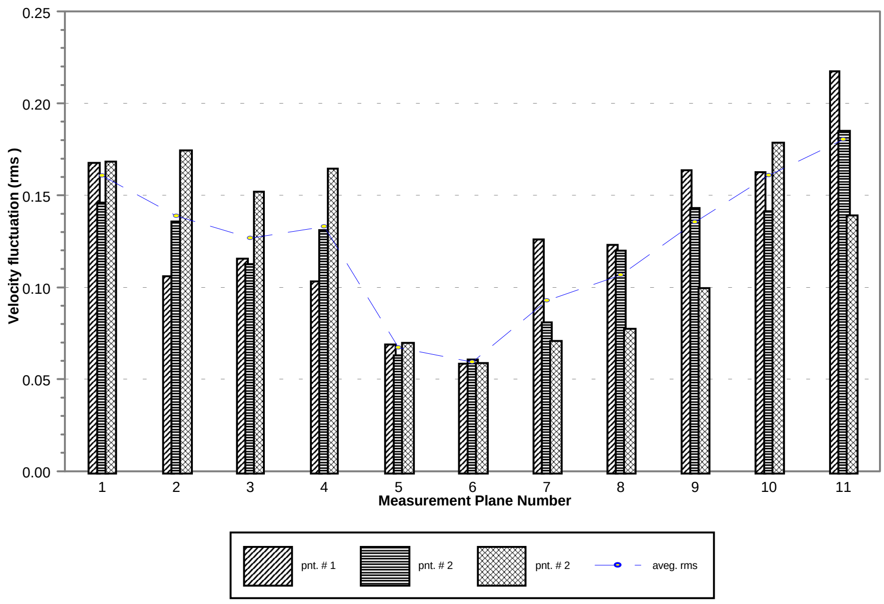


Figure 6. Velocity fluctuations, design flow.