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Free Vibration Analysis of a Model Piping System

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Abstract

This paper presents the first results of a benchmark programme to determine the seismic response of piping systems. The modal properties of a three-dimensional pipe model with built-in ends were determined experimentally and compared with the results obtained by finite element analysis using commercially available packages.

1. Introduction

The current trend in seismic plant design is for more exact analysis to take account of the non-linearities which must inevitably arise in a real situation. Initially time solution of the equations of motion was the preferred solution method but the computatonal power required to achieve this meant that this method was soon abandoned in favour of the modal analysis type of approach. Modal analysis is based on the concept of a linear system and relies on a determination of the principal modes of vibration of the system. The seismic analysis is only as good as the model that determines these fundamental modes.

To support the plant designer in the plant design process there are many computer analysis packages available based mainly on finite element techniques. When dealing with large installations such as power stations the designer has to rely upon the capability of both himself and the package to produce a good model for analysis purposes as there is likely to be little opportunity for full scale testing. The validation of theoretical results on full scale plant is obviously a difficult problem although some work has been carried out on selected items of plant [1] and has shown an acceptable degree of correlation between theory and practice. Such work has covered only a small part of this area of work and I felt that there was plenty of scope for a benchmark programme to investigate the correlation between experimental and theoretical results for a simple structure before moving on to more complicated structures.

The area of plant I decided to investigate in my benchmark programme was the pipework which would interconnect the major vessels in a large plant installation. A great deal of work has been carried out on the design of the major vessels in a plant and it is thought unlikely that they would fail in a seismic event; however the pipes connecting the vessels form a potential weak link in the chain and the failure of a pipe would be just as disastrous as a vessel failure. Therefore I decided to initiate a programme of work to check the correlation between theory and experiment for the dynamic analysis of a simple pipe system. This paper presents the results of the first part of the benchmark programme and concentrates on the free vibration analysis of the system.

2. Experimental Testing

Preliminary studies [2] had shown that in the analysis of process plant the modelling of the pipe intermediate supports was the most critical aspect in the analysis process. To try to eliminate as much uncertainty as possible in the correlation between theory and practice I decided to choose a model for the initial test programme which had no intermediate supports. The pipework model (Fig. 1) consisted of domestic copper pipe of approximately 21mm outside diameter. The bends were made from commercially available fittings and the ends of the pipe were "rigidly" built-in. A configuration extending into three dimensions was chosen so that both in-plane and out-of-plane effects would be present. The whole system was mounted on a 25mm thick base plate so that the complete model could be seismically tested at a later date.

The natural frequencies of the pipework model were determined experimentally by means of a sine-sweep test and plotting the resulting data on a Bode diagram. The frequency range investigated was from 0 to 150Hz and the excitation was applied both vertically and horizontally to the horizontal legs of the pipework (Fig.1). The acceleration/force and phase angle were plotted against frequency and a typical plot is shown (Fig.2). The indicated natural frequencies are shown in table 1. An estimate of the damping ratio was also obtained at a frequency of 14 Hz using the half-power method. This was found to be 2.9%.

3. Theoretical Model

The system was modelled using the elements and analysis procedures of two commercially available finite element packages PAFEC and ABAQUS. An initial static analysis was performed to determine if the proposed experimental model would be rigid without any intermediate supports. The dynamic analysis of the model was then carried out to determine the natural frequencies and mode shapes of the pipework.

The static model and the initial dynamic model used the Euler-Bernoulli beam elements, which do not allow for shear effects, and also ignored the bends treating them as right angles. The number of elements used was governed by the recommended length to diameter ratio of 5 to 1 which, for the dimensions of the model, resulted in elements 100mm in length and 23 elements in total. The ends of the pipework were assumed to be rigidly built-in and allowed no rotation or translation at the end nodes.

The second model used the Timoshenko beam elements, which allow for shear effects, and the bends were modelled using both the curved beam elements and elbow elements available in the two packages. Again the end nodes were rigidly built-in against rotation and translation. Finally a series of tests were performed to check the accuracy of the model in predicting the lowest natural frequencies using varying numbers of elements.

The results of the different finite element analyses are shown in table 2. A further series of test runs was carried out to determine the number of elements required to converge onto the lowest natural frequency, the second lowest natural frequency, etc. These tests showed that at the lower frequencies being investigated here the convergence was very rapid and that the number of elements used to obtain the results in table 2 were acceptable.

4.Discussion

The results of the experimental and theoretical analyses are shown in tables 1 & 2. The theoretical results show a good agreement with each other, the exception being the elbow element analysis which predicts lower frequencies than the other analyses. This is to be expected as the elbow element is more flexible than the other elements. It also shows how sensitive the theoretical model is to the change in stiffness in the bends. The mode shapes show very good agreement with the exception of the fifth frequency in the horizontal plane using the elbow element.

In the experimental testing there were four natural frequencies found in the vertical plane and five in the horizontal plane. The correlation between the theoretical and experimental results is good in the vertical plane at frequencies up to 100Hz but one of the predicted frequencies has not been found experimentally in the range from 100-150Hz. The correlation of results in the horizontal plane is poor at the two lower frequencies but the three higher frequencies predicted are quite clearly present although the numerical values are not exactly the same. It is difficult to see what has happened at the lower frequency. The 24Hz (experimental) could be the 29Hz (theoretical) in which case the lower 13Hz has been missed and the 58Hz is a spurious (but consistent) reading.

An important area of uncertainty between theory and practice which could be affecting these results is the pipe supports. In theory they were assumed to be rigidly fixed but there is obvious practical difficulty in ensuring that the ends are indeed rigid. To determine the effect of the pipe supports the pipe model will be tested in the next stage of the programme as a rigid body ie. without its supports.

The value for viscous damping of 2.9% compares well with the Regulatory Guide 1.61 [3]

Safe Shutdown Earthquake value of 2% for small diameter piping systems.

5. Conclusion

For the small diameter piping system tested the correlation between theoretical modelling and experimental testing was found to be generally acceptable although there were one or two spurious results which have still to be explained. At the lower "seismic" frequencies the elbow element appeared to give the better results and the experimental value of viscous damping agreed with the Regulatory Guide recommended value.

6. References

/ 1 / BARTA, D.A., ANDERSON, M.J., SEVERUD, L.K., "Seismic testing and analysis of a prototypic nonlinear piping system", American Society of Mechanical Engineers, NY, 82-WA.PVP-6.

/ 2 / Internal Reports, Glasgow College of Technology, 1982-1984.

/ 3 / Regulatory Guide 1.61, "Damping Values for Seismic Design of Nuclear Power Plants", U.S. Atomic Energy Commission, October 1973.

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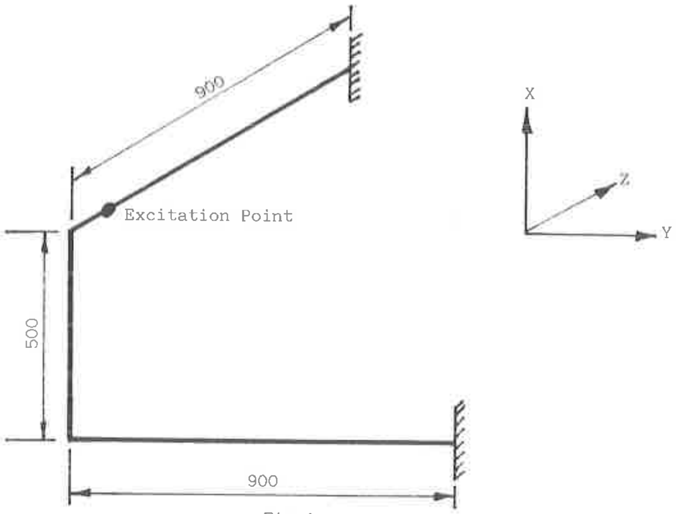

Fig 1.
Diagram of pipe model.

PIPE RIG (SHAKER VERT)

Shaker at node...16 Accel at node...16

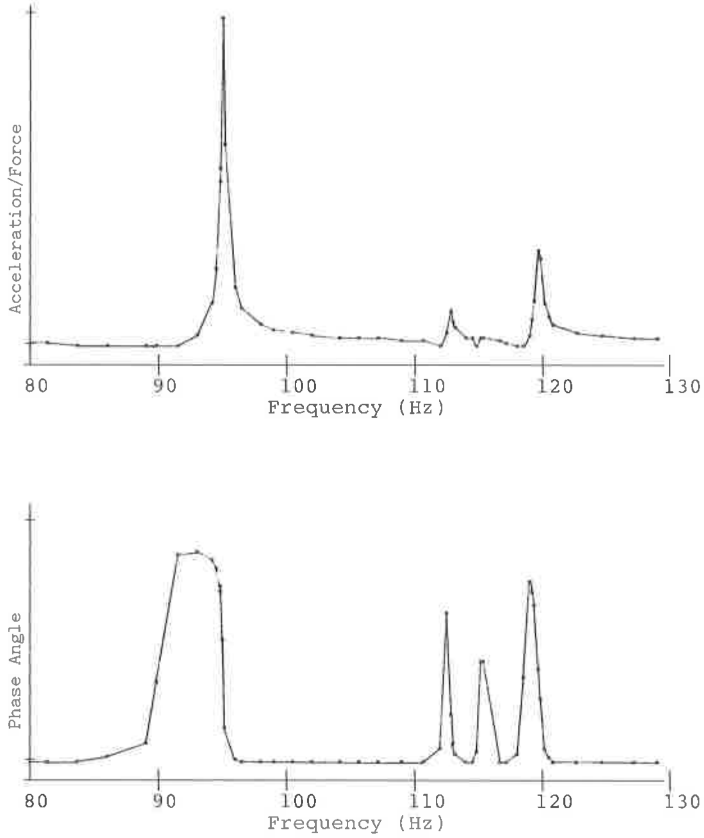

Fig.2.

Typical acceleration/force & phase against frequency diagrams.

Table 1: Experimental Natural Frequencies (Hz).

Vertical Excitation	14,26,95,120.
Horizontal Excitation	24,58,112,115,118.

Table 2: Theoretical Natural Frequencies (Hz).
Horizontal & Vertical

Euler-Bernoulli Beam	13.6,29.6,90.5,112,115.
Timoshenko Beam & Curved Beam	13.6,29.7,89.9,110.9,113.9.
Timoshenko Beam & Elbow	13.4,25.1,84.7,101.9,102.5.