inter-noise 96
25th Anniversary Congress – Liverpool

INCE: 76.9

NUMERICAL SIMULATION STUDIES OF INVERSE METHODS FOR QUANTIFICATION OF SOUND TRANSMISSION ALONG FLUID-FILLED PIPES

C A F de Jong & M H A Janssens

Acoustics Department, TNO Institute of Applied Physics, Delft, the Netherlands

1. INTRODUCTION

Pipes, carrying fuel, lubrication, cooling-water, etc. , constitute a path for structure- and fluid-borne sound transmission from machinery. Experimental methods are being developed, to be able to quantify the contribution of this path to the total sound transmission [1]. Practical application of these methods involves numerical inversion of matrices of measured transfer functions from a number of externally applied forces to either vibration or vibro-acoustic power flow at a number of positions in the piping. In addition to experimental tests performed earlier, the reliability of these methods has been investigated by means of numerical simulation studies, using the computer code *PRESTO* [2].

2. SHORT DESCRIPTION OF *"PRESTO"*

PRESTO calculates the vibro-acoustic response of three-dimensional fluid-filled pipe systems, using the Transfer Matrix Method [3]. Each component of the pipe system (e.g. straight pipe, elbow, pipe support, etc.) is described by a transfer matrix, that relates the structural vibrations and fluid pulsations at its outlet to those at its inlet. The complete pipe system is then described by a system matrix that follows from successive multiplication of the component transfer matrices. *PRESTO* is valid in the frequency range where the pipe diameter is small compared with the acoustic and structural wavelengths. In this frequency range vibro-acoustic energy is transmitted along straight pipes in five wave types: plane pressure waves in the fluid and extensional, torsional and two orthogonal bending waves in the pipe wall. Fluid pulsations and pipe wall vibrations are coupled at discontinuities, like elbows and T-junctions, and via Poisson contraction of the pipe wall.

3. INVERSE METHODS FOR SOUND PATH QUANTIFICATION

These inverse methods consist of the following steps (see [1]):
(1) With the machine running, pipe responses (acceleration or power flow per wave type) are measured at *M* positions in the system, together with the radiated sound pressure at a receiver position.
(2) With the machine switched off, the pipe system is excited artificially at *N* positions, one by one, by means of a hammer or a shaker. For each excitation a set of transfer functions is measured: from excitation force to pipe response, at the same *M* positions as under (1), and from excitation force to radiated sound pressure, also at the same position as under (1).
(3) A set of equivalent forces is then determined, which would generate as closely as possible the same pipe responses as the machine does. This involves the (pseudo-)inversion of the *MxN* matrix of measured transfer functions from excitation force to pipe response.
(4) The radiated sound pressure which would be caused by this combination of equivalent forces is calculated using the measured transfer functions from excitation force to radiated sound pressure. Comparison with the radiated sound pressure measured under (1) indicates the relative importance of the transmission along the pipe.

The choice of the number and the locations of the equivalent force and response positions is arbitrary to some extent. The criterion used is that the number of force positions should relate to the number of vibrational degrees of freedom of the sound path, i.e. seven for a fluid-filled pipe (six for the pipe and one for the fluid). More response positions are chosen, to obtain an over-determined set of equations.

4. SIMULATION STUDIES

The simulated system Fig.1 shows the geometry of the simulated pipe system. The internal diameter of the water-filled steel pipes is 69 mm, the wall thickness 3 mm. The system is supported on five damped beams. One end of the system is closed by a massless end plate on a short rubber hose. Excitation of the system by a 'machine' is simulated by means of a unit translatory displacement of the end plate in three orthogonal directions simultaneously. The other end of the pipe system is terminated with the impedance matrix of an infinitely long straight fluid-filled pipe, to guarantee a substantial amount of energy flow.
Power flow Fig.2 shows the relative contributions of structure-borne and fluid-borne power flow at position "g". This ratio will vary along the system, due to fluid-wall coupling. Note that a negative ratio may occur, but the total power flow is always positive. The power flows are determined using two-channel cross-spectral density methods [2]. *PRESTO* calculates the actual power flow at each pipe cross-section, so that the accuracy of the two-channel method can be evaluated, see Fig.3. Here the

error in the bending wave power flow is due to the presence of nearfields at low frequencies. The inaccuracy in the longitudinal wave power flow is due to fluid-wall coupling via Poisson-contraction [4].

Typical accuracy of the inverse methods Figures 4 and 5 give typical examples of the accuracy of the results when applying the inverse methods to the simulated data. Because *PRESTO* does not calculate the radiated power, the results are compared with a set of vibrational responses that are not taken into account in the inversion (Fig.4) and with the total power flow in the system (Fig.5). In practice it will often be inconvenient to excite artificially, or even to measure, pressure pulsations. These examples demonstrate the accuracy of the inverse methods when fluid-borne sound, although present, is not considered in the inversion.

5. CONCLUSIONS

The inverse methods require the use of at least seven 'equivalent forces' to represent all the vibrational degrees of freedom of a fluid-filled pipe. These may be seven independent structural forces, if this set of forces is also able to excite the fluid, e.g. via fluid-structure interaction in an elbow. The method will yield an acceptable accuracy using only structure-borne equivalent forces, provided that all forces are applied before the first pipe support after the source. It appears to be unnecessary to measure the sound pressure in the fluid, as long as sufficient accelerometers are used to monitor the system behaviour. If the vibro-acoustic power that travels through the pipe system is monitored, instead of the acceleration response, the corresponding set of equivalent forces does not necessarily give a correct representation of the vibrational behaviour of the system. Nevertheless the method appears to yield a useful estimate of the radiated sound pressure level, even when only the power flow in bending waves is measured at a number of pipe cross-sections. The *PRESTO* computer code is shown to be an effective tool to investigate the reliability of the measurement methods considered. The possibility to calculate the complete vibro-acoustic behaviour of fluid-filled pipe systems makes it useful for the design and evaluation of other experimental techniques, e.g. active noise control.

REFERENCES

[1] J.W. Verheij, M.H.A. Janssens & D.J. Thompson, Proc. Noise'93, St.Petersburg, 55-60 (1993)

[2] C.A.F. de Jong, Analysis of pulsations and vibrations in fluid-filled pipe systems (PhD Thesis, TNO Institute of Applied Physics, 1994)

[3] E.C. Pestel, F.A. Leckie, Matrix methods in elastomechanics (McGraw-Hill, New York, 1963)

[4] C.A.F. de Jong & J.W. Verheij, Proc. 4th Int. Congress on Intensity Techniques, Senlis, 111-117 (1993)

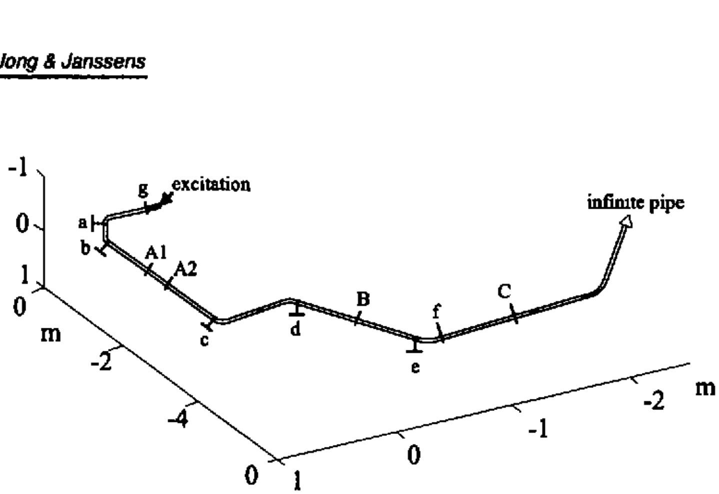

Fig.1. Geometry of the simulated pipe system, supports are indicated by "⊥". Vibrational responses are determined at the positions "a" to "f", power flow is 'measured' at the cross-sections "A1","A2", "B" and "C".

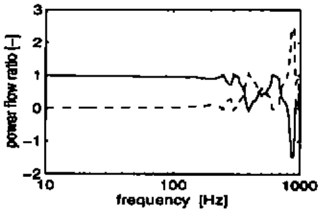

Fig. 2. Contributions of structure-borne (——) and fluid-borne (---) power flow at pipe cross-section "g".

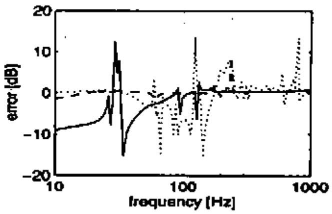

Fig. 3. Amplitude error for the two-channel measurements of power flow in bending (— and ---) and longitudinal (···) waves at cross-section "A1".

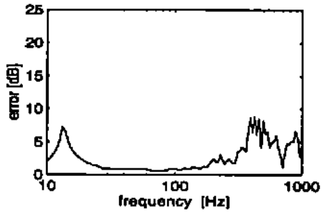

Fig. 4. Typical example of the average amplitude error for the vibration response based inverse method.

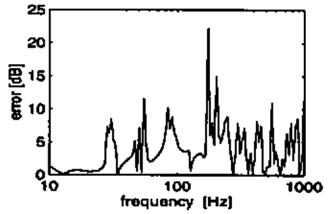

Fig. 5. Typical example of the amplitude error for the inverse method based on two-channel measurements of bending wave power flow.