Determination of Acoustic Sources Produced by Diaphragms in Turbine By-Pass Circuits

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ABSTRACT

This paper presents the development of an intensimetry method for plane waves which, from simple fluctuating pressure readings, determines information independent of the position of the measurement point, and dissociates the magnitudes specific to the source (source spectrum) from those linked to the circuit (reflection coefficient). The method is applied to an expansion circuit to select the less noisy of two diaphragm geometries.

1 - INTRODUCTION

The acoustic energy produced in large volumes by pressure reduction systems can cause severe vibration of structures which can escalate to rupture through fatigue. It is easy to grasp the interest of noise reduction downstream of diaphragms and in particular, the acoustic gain provided by a modification of geometry without altering load losses. The main difficulty of these parametric studies lies in the organisation of the arrangement of the generating source and the test circuit. The emission of acoustic waves (diaphragm), propagation (carrier fluid, circuit), multiple reflections (circuit) are all parameters whose combination acts on the spatial distribution of the final fluctuating pressure range. In these circumstances, it is difficult to characterize the source independently of the circuit by simple measurements and the use of a behavioural model becomes indispensable. The method followed relates to the propagation of one-dimensional longitudinal waves (plane waves) and is applied to a turbine by-pass circuit in a nuclear power station to enable a choice to be made between two different expansion diaphragm geometries.

2 - FORMULATION

The propagation of pressure fluctuations of a fluid in a piping occurs (at low frequencies) in the form of plane waves. Three-dimensional equations of the mechanics of fluids then reduce to one-dimensional equations.

Fluid state equation $$\delta p = c^2 \, \delta \rho \tag{1}$$

Continuity equation $$s \frac{\delta \rho}{\delta t} + \frac{\delta q}{\delta x} = 0 \tag{2}$$

Momentum equation $$s \frac{\delta p}{\delta x} + \frac{\delta q}{\delta t} + \frac{\delta}{\delta x} \left(\frac{\gamma q^2}{\rho s} \right) + \frac{K q^2}{2 \rho s} = 0 \tag{3}$$

Hypotheses

The influence of the viscosity of the fluid, whose effect is to reduce propagation at high frequency, is neglected. Flow viscosity is low by comparison with wave propagation speed. Flow is adiabatic and the fluid considered is a continuous medium. The coefficient K of the term $KQ^2/2\rho S$ representing the load loss produced by friction on the walls of the piping is obtained using the Niturades-Moody curves. The flow cross-section and the rate of flow per unit of mass are constant. Terms of order 2 are neglected.
Subscripts 1 designate fluctuations, 0 the steady state.

The equations then become:

$$\frac{\delta q_1}{\delta x} + \frac{i\omega s}{c^2} P_1 = 0 \qquad (4) \qquad\qquad P_1 = \rho_1 C^2 \qquad (5)$$

$$s \frac{\delta P_1}{\delta x} + 2\,\gamma v o \frac{\delta q_1}{\delta x} + (i\omega + Av_o)\, q_1 = 0 \qquad (6)$$

with, for a smoother turbulent flow

$$A = a/d \qquad (7)$$

and for a rough turbulent flow

$$(\, A = aRe^b/d \,) \qquad (8)$$

The solutions of the equations are of the form

$$P = \alpha e^{-k_1 x} + \beta e^{-k_2 x} \quad \text{and} \quad Q = \frac{S}{\rho c} (\alpha e^{-k_1 x} + \beta e^{-k_2 x}) \qquad (9)\ (10)$$

$$\text{with} \quad k_1 = \frac{i\omega}{c} \left(\gamma v/c + \sqrt{1 - \frac{iAv_o}{\omega}}\right) \quad \text{and} \quad k_2 = \frac{i\omega}{c} \left(\gamma v/c - \sqrt{1 - \frac{iAv_o}{\omega}}\right) \qquad (11)\ (12)$$

α representing the direct wave, i.e., circulating in the direction of flow and B, the reverse wave, i.e., circulating in the opposite direction to the flow.

The quantity $\gamma v/c$ is generally low and $1 - \frac{iAvo}{\omega}$ does not differ much from unity in most real cases; as a first approximation, we thus take:

$$k_1 = k_2 = k = \frac{2\pi f}{c} \qquad (13)$$

3 - APPLICATION OF THIS FORMULATION TO THE TURBINE BY-PASS CIRCUIT

In the event of a SCRAM at a nuclear power station, the turbine by-pass circuit is under severe stress. The function of this circuit is to allow ongoing cooling of the reactor by the secondary system in the event of turbine shutdown. Mounted in parallel to the turbine, the system should be scaled so as to expand the steam produced by the generator from 80 bar to 40 millibar (condenser pressure). The steam penetrates a cylindrical chamber (Figure 1) through a diaphragm (D1) in which the first expansion occurs. It is released from the cylinder via another diaphragm where it undergoes its second expansion.

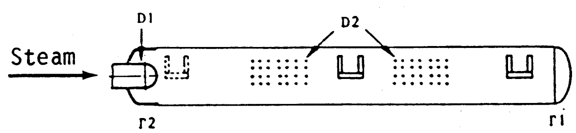


Figure 1 : Turbine by-pass circuit

The pressure fluctuations produces by D1 can be decomposed into (a) local non-propagating turbulent fluctuation in the frequency band 0 to 50 Hz and localised immediately downsteam of the diaphragm, and (b) propagating fluctuations which can be viewed as plane waves between 0 and 500 Hz considering the dimensions of the cylinder. The study is limited to the latter.

The minimization of the waves emitted by D1 is a major factor for reducing the stresses applied to the structure and thus guaranteeing the equipment an extended lifespan. This explains the tests conducted on two different geometries of the diaphragm (figure 2) which wave celerity in the fluid considered must be derived before identifying the source spectrum thus emitted and the reflection coefficients at both ends of the cylinder.

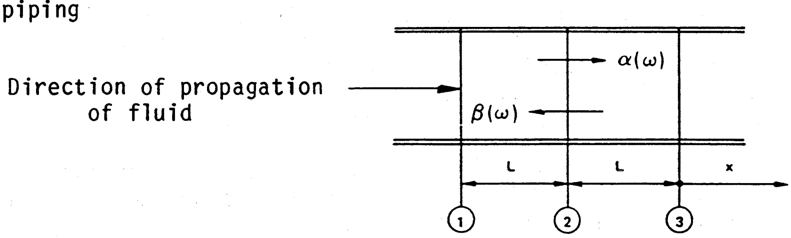
$D1_1$: Flat diaphragm
Number of holes > 100

$D1_2$: Hemispherical diaphragm
Number of holes < 50
Cross-section identical to $D1_1$

Figure 2 : Diaphragms D1 used

Determination of wave propagation speed

Assuming three pressure fluctuation sensors are laid out at regular intervals along the piping



The pressures and flowrates can be expressed in the form:

$$P2 = \alpha + \beta \qquad\qquad P3 = \alpha e^{-jkL} + \beta e^{jkL}$$

$$Q2 = \frac{S}{\rho c}(\alpha - \beta) \qquad\qquad Q3 = \frac{S}{\rho c}(\alpha e^{-jkL} - \beta e^{jkL})$$

$$P1 = \alpha e^{jkL} + \beta e^{-jkL}$$

$$Q1 = \frac{S}{\rho c}(\alpha e^{jkL} - \beta e^{-jkL})$$

The half sum of the transfer functions between sensors 1 - 2 and 3 - 2 is a frequency cosine function which, when the distance L is known, only depends on wave celerity (figure 3).

$$\frac{H12 + H32}{2} = \frac{P1 + P3}{2P2} = \frac{\alpha e^{jkL} + \beta e^{-jkL} + \alpha e^{-jkL} + \beta e^{jkL}}{2(\alpha + \beta)} = \cos kL$$

Smoothing by least squares yields the real value of wave propagation speed, since it is determined experimentally from the readings.

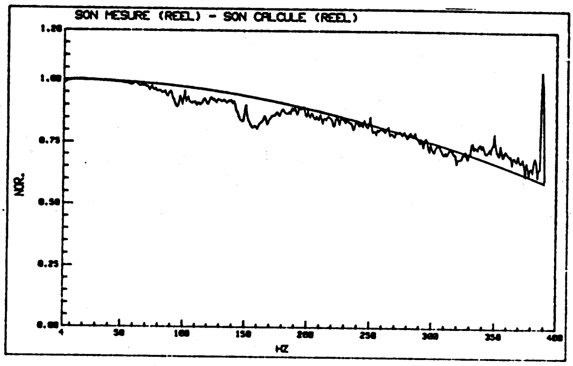


Figure 3 : Example of a cos k L = f (ω) function

Determination of the source associated with each diaphragm as well as the reflection coefficients of the ends of the cylinder

Of the above three data acquisitions, only two are needed for the determination of the characteristics of the source and the circuit. It is assumed that they are far enough from the diaphragm to be able to neglect the non-propagating turbulent fluctuations.

The fluctuation emitted by D1 is propagated to the end of the cylinder (reflection coefficient Γ 1) where it is reflected. The wave which has lost part of its energy propagates in the opposite direction to reach the other end of the cylinder (reflection coefficient Γ 2) where it is again reflected (figure 4). The reflection coefficients are assumed to be real and of constant frequency.

The combination of the incident wave and the multiple reflections form a quasi-stationary wave system which makes the fluctuating pressure data dependent on the position of the measurement point on the cylinder.

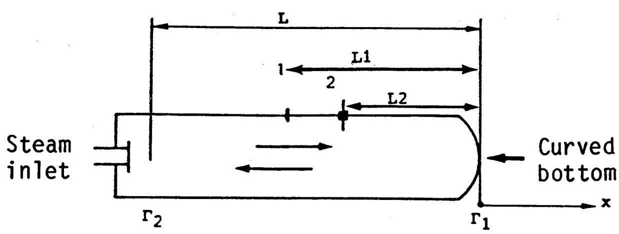


Figure 4 : Turbine by-pass circuit

Pressure at point 1 can be expressed in the form:

$$P1 = S \left(e^{-ikL_1} + \Gamma_1 e^{ikL_1} \right) x \frac{1}{1 - \Gamma_1 \Gamma_2 e^{2ikL}}$$

in which S represents the amplitude of the source spectrum.

The wave system thus observed is equivalent to an incident wave alone, hypothesized as being of variable amplitude, depending on the position in the cylinder whose value is between:

$$(1 - \Gamma_1) \frac{1}{1 + \Gamma_1 \Gamma_2} \quad \text{and} \quad (1 + \Gamma_1) \frac{1}{1 - \Gamma_1 \Gamma_2}$$

The reflection coefficient $\Gamma 1$ is directly determined from the pressure values recorded in 1 and 2:

$$\Gamma_1 = \frac{P1e^{-ikL_2} - P2e^{-ikL1}}{P2e^{ikL1} - P1e^{ikL2}}$$

The determination of reflection coefficient $\Gamma 2$ necessitates an additional hypothesis, that the source spectrum is constant in a frequency band exceeding the STROUHAL cut-off frequency. This hypothesis is found generally in the literature relating to the noise produced by diaphragms. The reflection coefficient is then deduced from the pressure equation by formulating the latter at various frequencies. The calculations show that the reflected wave arriving on the diaphragm is absorbed in the case of the flat diaphragm (certainly dislocated by local turbulence) whereas it is once again reflected in the elliptic case.

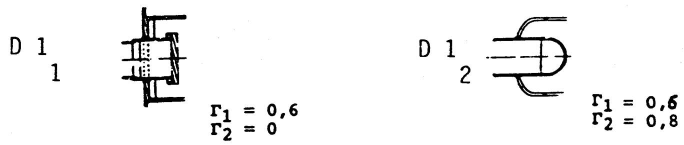


Figure 5 : Reflection coefficients of the circuit

Armed with the reflection coefficients, the calculation of the source spectrum is immediate and shows that in both cases, the source is dominant at low frequency up to the STROUHAL cut-off frequency. It becomes constant in the higher band up to the limit of validation, of plane waves (approximately 500 Hz); these findings correspond to the literature. The source amplitudes relating to each diaphragm design show a difference of factor 10 in favour of the hemispherical diaphragm.

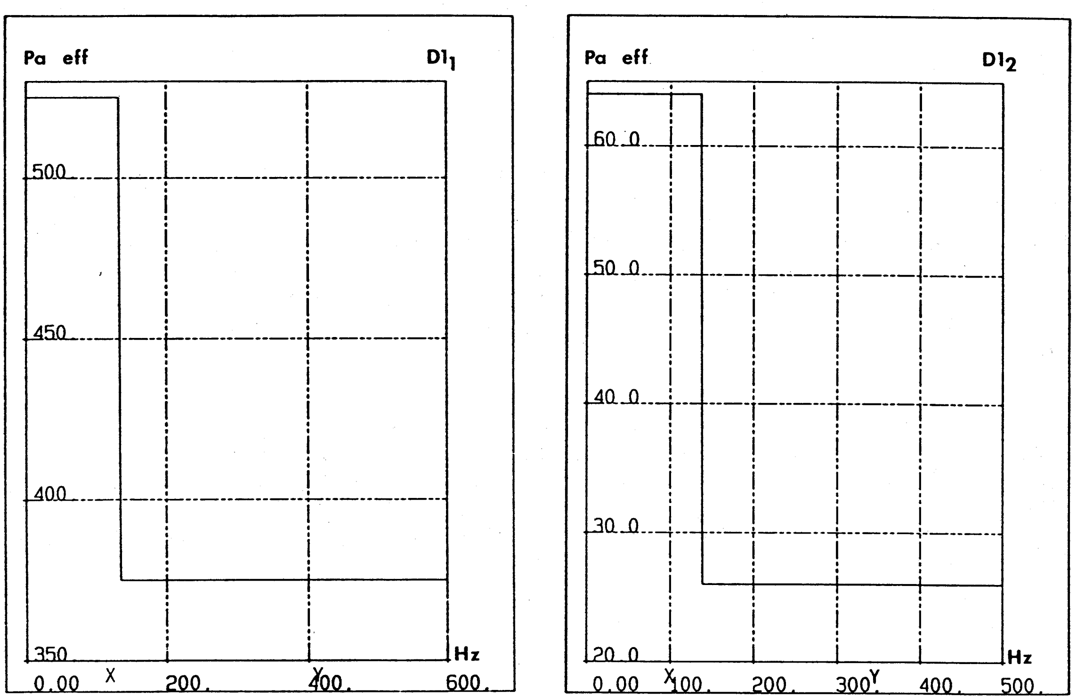


Figure 6 : Source spectra obtained using the model

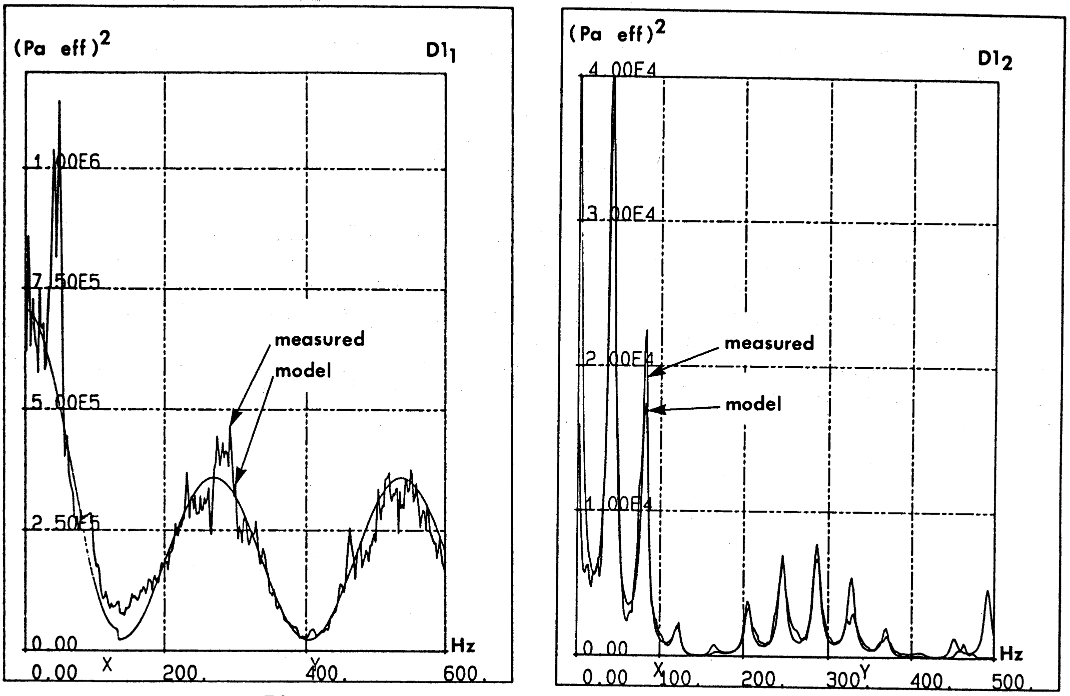


Figure 7 : Pressure fluctuation spectra : comparison between measurement and modem

4 - CONCLUSION

Gross fluctuating pressure readings cannot be used because they depend on the position of the sensor. Intensimetric processing does away with the measurement problems arising from stationary or quasi-stationary waves and separates the data relating to the source (source spectrum) from those relating to the circuit (reflection coefficient). The development of these methods for testing two expansion diaphragms with different geometries designed to be fitted in a turbine by-pass circuit of a nuclear power station has disclosed two different behaviour phenomena.

The flat diaphragms with a large number of holes produces plane waves whose amplitude is ten times greater than those emitted by hemispherical diaphragms with a small number of holes. The wave reflected by the bottom of the cylinder (reflection coefficient 0.6) is absorbed by the flow immediately downstream of the flat diaphragm (reflection coefficient close to 0), whereas it is reflected anew by the hemispherical diaphragm (reflection coefficient 0.8), the combination of incident and reflected waves forming a quasi-stationary wave system in both cases.

In the case of the hemispherical diaphragm the low emission level of acoustic waves in the zone of mechanical frequencies of the structure makes this diaphragm particularly attractive by comparison with the flat diaphragm. In particular, the effect of the gain on the source on the level of dynamic stress of the cylinder extends the lifespan of the equipment substantially, bearing in mind that it is already subject to other intense stresses.

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