SIMULATION OF THE ORIFICE GAUGE LINE EFFECT IN PULSATING FLOW

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1. Introduction

Gauge line response to pressure pulsation at the orifice plate taps distorts pressure signals and affects pressure difference applied to the diaphragm of a differential transmitter (Fig. 1). This response depends on gauge line length L, volume V_o of the transmitter chamber, pulsation frequency f, and amplitude $|P_p|$. Distortion of the pressure difference ($\Delta p = p_{p1} - p_{p2}$) by the gauge line obviously affects accuracy of flow rate metering. In order to eliminate significant errors, the gauge line response was simulated with lumped parameter model and plane wave model. Connectors on the gauge line, however, constitute abrupt variation of the inside diameter, affecting propagation and attenuation of the disturbances. Moreover with high velocity amplitudes turbulent regime occurs. These factors preclude pure theoretical description of the gauge line response and make some empirical contribution necessary. Utilizing experimental results damping coefficients were determined for two models with various gauge line length, chamber volume, pulsation frequency, and amplitude. Oscillating pressure difference across the orifice plate was simulated and compared with the monitored one.

2. Experiment

Frequency and amplitude of pressure pulsation was controlled by flow velocity in the test line and by the speed of a rotating disc installed on the line. Oscillating pressures were monitored with four high frequency response transducers (Endevco). The measurements were taken with three gauge lines of a different length L (0.166, 1.118 and 3.118 m) and in the frequency range 5 - 180 Hz.

3. Theory

Lumped Parameter Model

In this model [1] the tube and volume are regarded as capacitance, momentum equation takes into account inertance and resistance, and boundary conditions are nonlinear. Differential equation of forced vibration was obtained

$$(1)\quad d^2p_t / dt^2 + 2\theta |dp_t / dt| dp_t / dt + \omega_o^2 p_t = \omega_o^2 p_p \ ,$$

where damping factor

$$(2)\quad \theta = (1 + L_o / L)(1 + \zeta + \lambda L / d) / 4\gamma p_o \ ,$$

natural frequency of undamped oscillation

$$(3)\quad \omega_o = 2\pi f = a_o / \left[L (1 + L_o / L)^{1/2} \right], \qquad L_o = 4V_o / \pi d^2 \ ,$$

ζ - coefficient of inlet pressure loss, λ - coefficient of friction, γ - isentropic exponent, p_o - mean gas pressure and a_o - mean sound speed.

Plane Wave Model

Transfer matrix for the tube of L length yields the oscillating pressure ratio

$$(4)\quad P_p / P_t = \cosh(ikL) + (ikL)(L_o / L)\sinh(ikL)$$

where according to Kirchoff's derivation $ik = \alpha_L + i(k_o + \alpha_L)$, $k_o = 2\pi f / a_o$ and

$$(5)\quad \alpha_L L = (k_o L)^{1/2} \left[(2L / d) / Re_a \right]^{1/2} \left[1 + (\gamma - 1) / Pr^{1/2} \right]$$

$Re_a = \rho_o a_o d/\mu$, ρ_o - mean gas density, μ - dynamic viscosity and Prandtl number $Pr = \mu c_p / K$. Omission of damping in (4) and introduction of resonance condition provides natural frequency of oscillation

$$(6)\quad (k_o L) \tan (k_o L) = L / L_o$$

4. Numerical Simulation

For simulation purpose the complex geometry of the system was simplified by substituting the gauge line with the variable cross-section by the uniform cross-section tube with the equivalent diameter.

Lumped Parameter Model

The coefficients θ and ω_o were calculated from Eq. (1) using pressure-time traces measured in the transducer chamber and pipe. The multilinear regression method was applied to obtain coefficient values which ensure the best fit (minimum standard deviation) between both pressure signals. Natural frequency ω_o depended only on the system geometry, i.e. on the transducer chamber volume, length and equivalent diameter of the gauge line, what is in agreement with the theory. Attenuation coefficient θ was little dependent on the frequency and amplitude of pressure oscillation, as well as on the gauge line length (Fig. 2). Simulated and measured pressure p_{p1} (Fig. 3) and pressure difference Δp across the orifice plate agreed within ~1%. It was found that model accuracy only slightly decreased with the increasing frequency and amplitude of pressure oscillation but it deteriorated completely for the longest gauge line.

Plane Wave Model

In order to take into account the turbulent damping, the laminar attenuation coefficient was replaced by the effective coefficient $\alpha = n \cdot \alpha_L$ in Eq. (4), and calculated using the amplitude ratio of the first harmonics measured in the pipe and transducer chambers. For the lowest frequency and the shortest gauge line multiple α values occurred for a given pressure ratio. The value with the best approximation of the phase angle between the pipe and transducer pressures was selected for further calculations. As Fig. 4 shows, increasing attenuation suppressed $|P_t/P_p|$ and shifted it to lower k_oL value. Maximum α/α_L increased with the gauge line becoming shorter (Fig. 5). Simulated and measured pressure differences Δp are compared in Fig. 6. The model gave good prediction of the pipe pressure amplitudes, but not always accurate estimation of phase angles.

5. Conclusions

Numerical simulation showed different assets and limitations of both models:

- Lumped Parameter Model considers the overall oscillating pressure level and is not restricted to a single harmonic. However, its range of application is limited to a short or medium length of gauge lines ($L \leq 1.2$ m)
- Plane Wave Model simulated only the amplitude of the first pressure harmonic. Its application was not constrained by the length of the gauge line. Disadvantage results from a low accuracy of the phase shift prediction and omission

of higher harmonics what affects particularly Δp calculation

- Accuracy of both models declines with increase in frequency, but was not affected by the pressure amplitude in the range monitored.

Generally, simulation with high accuracy of the pressure in the pipe using the pressure signals measured in the transducer chamber was feasible for some ranges of basic parameters.

6. References

1. Nagao, F. and Ikegami, M., "Errors of an Indicator Due to a Connecting Passage", Bulletin of JSME, Vol. 8, No. 29, 1965, pp. 98 - 108.
2. Tijdeman, H., "On the Propagation of Sound Waves in Cylindrical Tubes", J.S.V., Vol. 39, No. 1, 1975, pp. 1 - 33.

Acknowledgement

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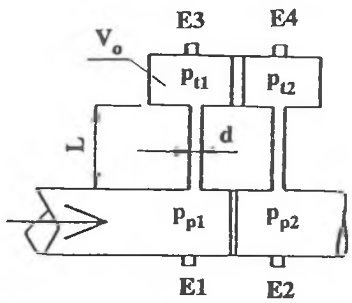

Fig. 1

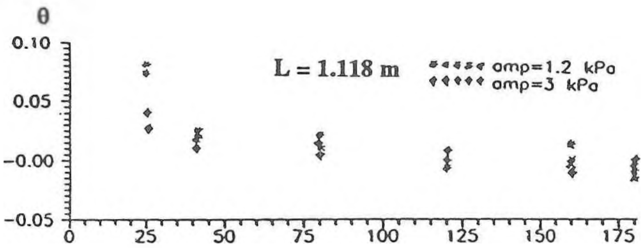

Fig. 2

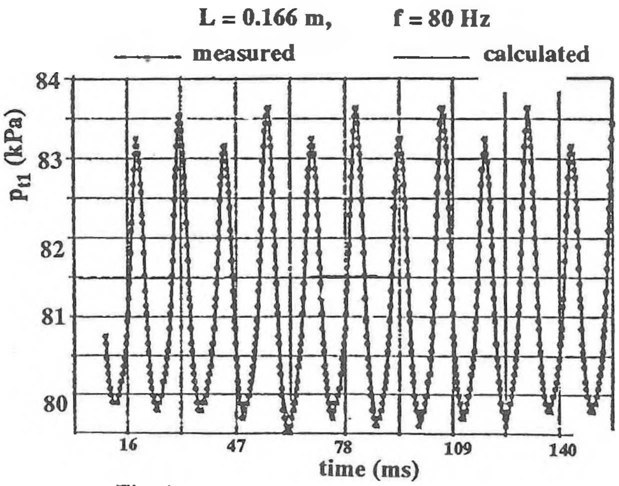

Fig. 3

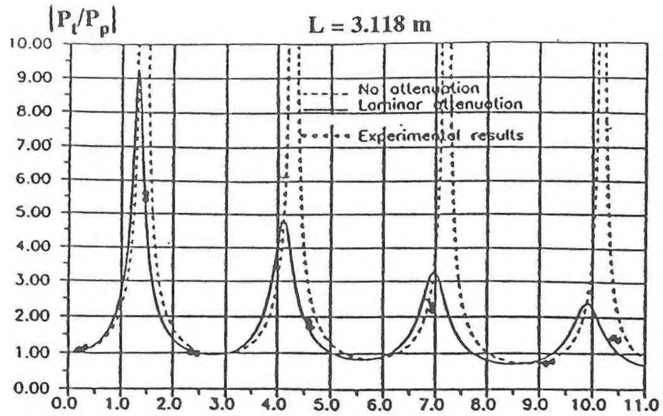

Fig. 4 k_oL

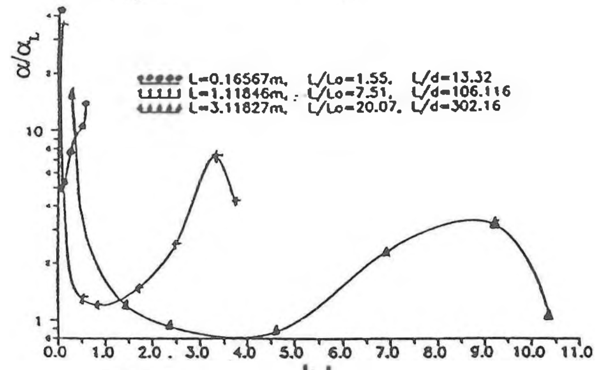

Fig. 5 k_oL

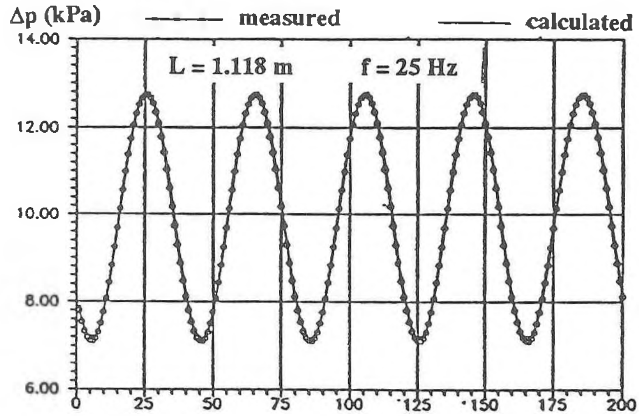

Fig. 6a

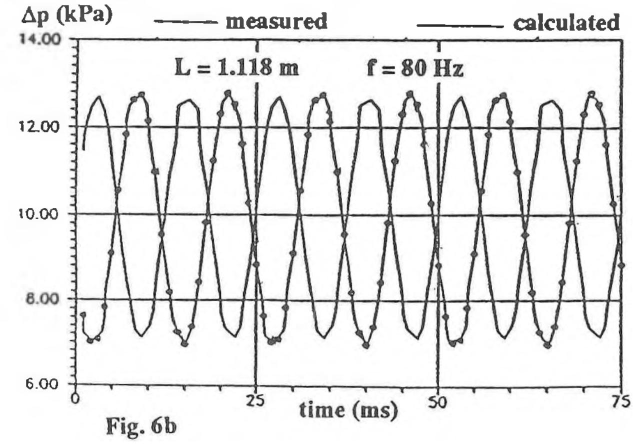

Fig. 6b