Acoustic Energy Concept for the Design of a Flow Meter

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An acoustic energy source concept is used to develop simple theoretical expressions for the optimisation of the dimensions for the design of a flow meter. Basic equations are first generated for the prediction of vortex shedding frequency due to a bluff body placed inside a pipe or a channel flow. The Strouhal number predicted using these expressions is compared with limited experimental data for a 6-inch commercial vortex flow meter operating at different Reynolds numbers. The results show good agreement between theory and experiment.

NOMENCLATURE

a — speed of sound
A — a non-dimensional parameter
C — characteristic length of a bluff body shedding vortices
d — diameter of a circular cylinder
D — diameter of pipe or channel width
f — vortex shedding frequency
N — an integer
P — perimeter of the vortex shedding body
S_R — Strouhal number ($=fd/U_\infty$)
U_V — velocity associated with vortex street
U_∞ — free stream velocity
X — spacing between two consecutive vortices of the same row
Y — spacing between two parallel rows of vortices
K — circulation of vortices

1. INTRODUCTION

Measurements in fluid mechanics are carried out using a multitude of techniques.[1-3] The measurement of flow rates using devices commonly known as 'flow meters' is one of the most common measurements made in flowing fluids, such as in pipes. Flow meters, however, use a variety of different principles to measure volume flow rate. One such principle is vortex shedding caused by a bluff body. It has long been known[4] that the sound frequency produced by a translating cylindrical rod is related to a characteristic length of the body and the velocity of the flow. There are several commercial flow measurement devices that use this principle to quantify mass or volume flow rates through pipes or channels. There is a general consensus that vortex shedding is the consequence of instability in the boundary layer on a body and is dependent on the Reynolds number of the flow. The treatment of boundary layer, however, poses formidable problems, conceptually, theoretically and experimentally.[5-8] Consequently, the design and development of vortex meters has evolved by trial and error or in an empirical manner.

In this paper, an alternative approach is explored which can produce easy to use expressions that can be exploited in the design of a stable and linear vortex flow meter. The approach is based on acoustic energy considerations. As far as the author is aware, this is the first and novel application of such an approach in the design of a flow meter.

2. BASIC CONCEPTS

The problem of vortex shedding can be viewed as an acoustic energy effect in the wake.[9-11] The basic assumption behind this consideration is that the velocity fluctuations in a turbulent wake and the fluctuating surface pressure stresses at the body surface act as acoustic sources. The sound intensity of these sources varies to the eight power of the relative fluid velocity. For alternate vortex shedding such as on a circular cylinder, three centres of disturbances can be identified: two strong areas at the separation points and a weak one at the stagnation point. Acoustic pressure pulse sources can then be considered concentrated at these centres. The frequency of the vortex pair can be assumed to be given by:[12]

$$f = \frac{3}{2P}(U_\infty - U_V). \qquad (1)$$

No practical method was suggested in reference[12] to determine U_V. Consequently, this expression has rarely been used.

Using well known hydrodynamic principles, however, a theoretical expression of U_V can be obtained for two parallel rows of vortices of the same spacing, X, but of opposite circulation K. The vortices are so arranged that each vortex of the upper row is directly above the mid point of the line joining two vortices of the lower row and are separated by a distance Y. Under such conditions, the velocity of the vortex street, U_V is given by:[13]

$$U_V = \frac{K}{2X}\tanh\left(\frac{\pi Y}{X}\right). \qquad (2)$$

When the bluff body producing alternate vortices is placed inside a pipe, the velocity contribution due to the wall effect becomes KY/XD, where D is the diameter of the pipe or width of the channel. The general stream in the distant wake assumes a velocity equal to ($U_\infty KY/XD$). Consequently, the frequency of vortex shedding can be written as:[14]

$$f = \frac{1}{X}\left(U_\infty + K\frac{Y}{XD} - U_V\right). \qquad (3)$$

From Eqs. (2) and (3):

$$f = \frac{U_\infty}{X}\left[1 - \frac{U_V}{U_\infty}(1 - G)\right], \qquad (4)$$