International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:9, No:8, 2015

Estimating the Flow Velocity Using Flow Generated Sound

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***Abstract*—**Sound processing is one the subjects that newly attracts a lot of researchers. It is efficient and usually less expensive than other methods. In this paper the flow generated sound is used to estimate the flow speed of free flows. Many sound samples are gathered. After analyzing the data, a parameter named wave power is chosen. For all samples the wave power is calculated and averaged for each flow speed. A curve is fitted to the averaged data and a correlation between the wave power and flow speed is found. Test data are used to validate the method and errors for all test data were under 10 percent. The speed of the flow can be estimated by calculating the wave power of the flow generated sound and using the proposed correlation.

***Keywords*—**Flow generated sound, sound processing, speed, wave power.

I. Introduction

DESIGN of modern fluid systems relies heavily on flow parameters. Present day laboratory and field research in fluid dynamics often requires flow velocity measurements with a high temporal and spatial resolution. In all of industries, increasing attention is being paid to developing innovative measurement techniques which are essential for successful design and control of the systems [1].

Recently, various measuring techniques have been developed in laboratory studies [2]-[5]. Air flow velocity measurement is associated with a variety of technical difficulties [6]. In most cases, features of the flow and operational challenges and costs of the measuring techniques are the limiting factors for the feasibility of such techniques.

Lots of researchers have investigated flow generated sound. Lighthill [7] developed a theory based on the equations of motion of a gas for the purpose of estimation the sound radiated from a fluid flow, with rigid boundaries, which as a result of instability contains regular fluctuations or turbulence. Based on Lighthill's acoustic analogy, [8] presented Numerical computations of sound generated from flows with a low Mach number with an assumption that sound does not alter the flow field from which it is generated. Wang et al. [9] reviewed the computational methods to predict the sound generated by airflow and the underlying theories. In their review, numerical methods and modern flow simulation techniques are discussed in terms of their suitability and accuracy for flow noise calculation. Roux et al. [10] studied turbulent flow within a complex swirled combustor with compressible large eddy simulation (LES), acoustic analysis, and experiments for both cold and reacting flows. Surek [11] investigated flow-generated sound and velocity distributions of free flows which are characterized by frequency spectra, by the PSD and wavelets. Garcia et al. [12] analyzed the capability of acoustic Doppler velocimeters to resolve flow turbulence. Results showed that this technique has some restrictions in particular conditions. Davies et al. [13] worked on the problem of estimating the sound field generated by a limited region of turbulence in an infinitely long, straight, hard-walled pipe. Their results demonstrated that the sound increase with specific power of velocity in different conditions.

Airflow can influence sound waves in a duct through different phenomena such as pressure fluctuations [14], [15]. However these effects are so complex that cannot be investigated analytically. Thus, an experimental analysis is needed to determine the exact effect of airflow on sound characteristics. As a practical utilization of this relation, it can be used successfully in other technical areas, in particular in the field of flow measurement as described below

The basis of the flow velocity measurement technique proposed in this paper is to find the relationship between sound power and velocity and then to use this relation estimate the velocity for the measured sound epower. To the best of our knowledge, so far, there is no comprehensive study to use this relation between sound power and the flow mean velocity in a duct as a measuring method.

No doubt, a simple and accurate flow velocity measurement technique can reduce operating costs without sacrificing performance. Furthermore such techniques can be used for particular situations in which other conventional flow velocity measurement techniques cannot be used.

The aim of this work is to provide a correlation between the velocity of airflow and sensed sound within a duct which can be used as an alternative approach for flow rate measurement. This technique is relatively low in cost and acceptable in accuracy and has relatively simple operational conditions. In the following the acoustic effects of airflow on sound waves generated by embedded microphones are analyzed and outlined.

II. Experimental Set Up

To define the air flow velocity from flow-generated sound some sample data are required. Sounds of flow for particular velocities are recorded and used as a database to define the

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relation between flow velocity and flow generated sound. A part of sample is taken as test for method validation. Database contains 120 flow recorded sounds which 10 percent of it is taken as test data. All air flow velocities are in low Mach range.

The schematic of experimental set up is illustrated in Fig. 1. A microphone is placed in the air flow to record the flow generated sound, a short length 10 cm diameter tube is placed right before the microphone to reduce the unwanted fluctuations of flow direction and to make the flow direction normal to microphone. The recorded sound is transferred to a computer for further analyses. Due to data analyses, the noise was negligible in compare to flow generated sound.

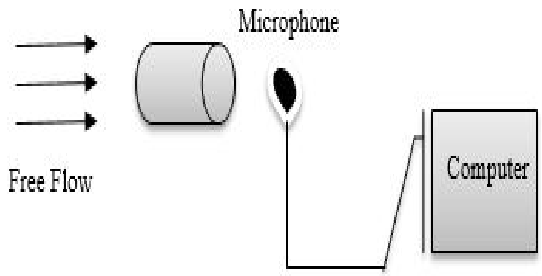

Fig. 1 Experimental set up schematic

III. Data Analysis

All samples data rates are 16000 Hertz, it means a 1 second sample contains 16000 quantity between -1 and 1. Figs. 2-4 illustrate the recorded sound waves for 20, 50 and 80 km/h velocities.

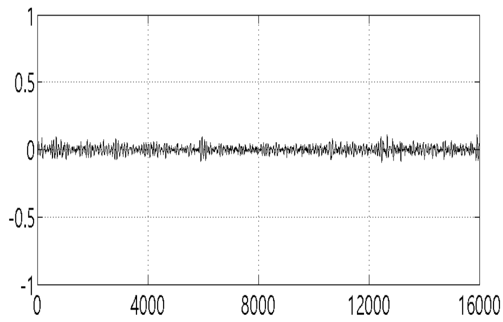

Fig. 2 Flow generated sound for speed of 20km/h

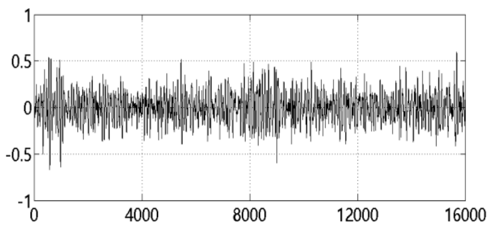

Fig. 3 Flow generated sound for speed of 50km/h

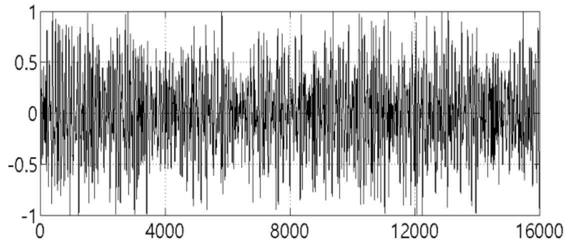

Fig. 4 Flow generated sound for speed of 80km/h

As it can be seen the amplitude of the waves are increasing as the velocity increases.by comparing two different velocities it is clearer. Fig. 5 compares the sound generated by 40km/h and 90km/h flows. The dark blue is the lower speed.

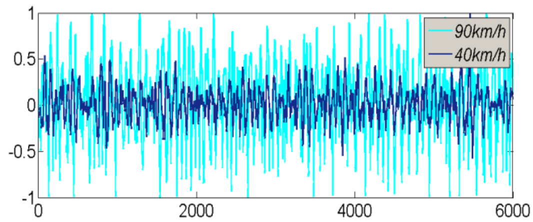

Fig. 5 Flow generated sound for two velocities

Fig. 6 compares two samples with the same velocity. Although the waves are not the same but the range of amplitudes are almost the same. Under similar experimental conditions the results for each velocity are identical.

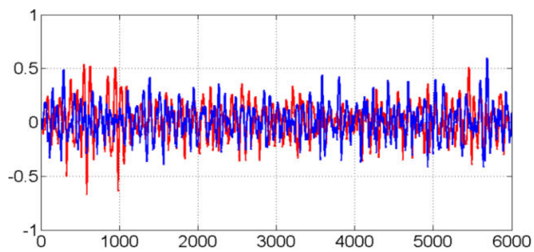

Fig. 6 comparing two samples of 50km/h speed

Now, it should be decided which parameter can be used to define the velocities. Assume each second of the sample to be a vector containing 16000 numbers between -1 and 1. As the velocity increases the amplitudes of the waves increase and as a result this 16000 numbers of higher velocity have higher maximums than the number of the lower velocity. So the summation of absolute value of each element in the vector can be an acceptable parameter. This parameter is affected from both amplitude and frequency. It will be called wave power.

After selecting the appropriate parameter it will be checked for all gathered sample data, Fig. 7 shows the wave power of all samples for different velocities. As it can be seen almost in all cases the error is not large in value.

Averaging the wave powers for each velocity gives us a magnitude for wave power of each velocity magnitude. These values will be used to predict the flow velocity by its generated sound. A two dimensional curve will be fitted to this discrete numbers to relate the flow velocity to intensity of sound wave generated by the flow. The average value of wave powers for different velocity magnitudes and maximum percentage of averaging error are shown in Table I.

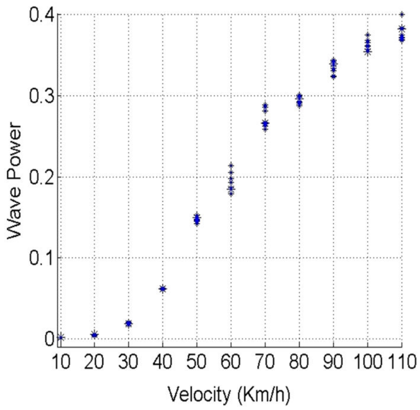

Fig. 7 Velocity vs. wave power for all samples

TABLE I
AVERAGING

Velocity (km/h)	Wave Power Average	Maximum Error Percentage
10	0.0018	**7.64**
20	0.0049	**9.38**
30	0.0185	**8.00**
40	0.0617	**2.36**
50	0.1465	**3.61**
60	0.1931	**10.57**
70	0.2716	**6.17**
80	0.2938	**2.42**
90	0.3338	**3.16**
100	0.3634	**2.99**
110	0.3770	**5.98**

IV. Results and Discussions

A curve is fitted to the values of wave powers with respect to velocities. The outcome equation can be seen in equation 1 where V is velocity in km/h and P is sound wave power and the coefficients of the correlation are listed in Table II. The r square and sum of square errors of the fitting are 99.78 and 0.00047 and both are in acceptable range.

$$lnV = a + bP + cP^2 + dP^3 + eP^4 \quad (1)$$

TABLE II
COEFFICIENTS OF (1)

coefficient	value
a	-12.6542451
b	0.475331196
c	-0.00769009
d	5.70673e-05
e	-1.606e-07

Fig. 8 illustrates the fitted curve and the average values of the wave powers with respect to flow speed.

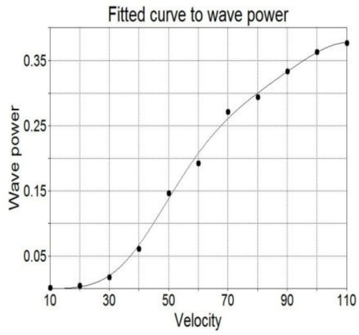

Fig. 8 Average wave power vs velocity and the fitted curve

Now the test data are used to check the correlation. Wave power for each sample is calculated and the value of velocity magnitude from the correlation and the experiments are compared. The results are shown in Table III.

TABLE III
VALIDATION

Velocity	Error percentage
10	9.07
20	8.21
30	7.20
40	7.58
50	6.94
60	3.42
70	0.29
80	3.97
90	4.35
100	0.91
110	1.68

As it can be seen in Table III, error percentage in all cases is under 10 % so the accuracy of the results are acceptable. In lower speed the accuracy is lower because of the noises in the sound samples.

It should be noted that only the low Mach flows are investigated and the curve is also fitted for speeds lower or equal to 110 km/h.

V. Conclusions

The flow generated sound of many cases is studied to develop a relation between the flow speed and the sound, generated by flow. Some parameters are investigated and at last the wave power is chosen to be the working parameter. Wave power for all sample data are calculated and averaged for each flow speed. Curve fitting leads to a correlation between wave power and the flow speed. Test data are used to validate the method and the error in all cases were below 10 percent. The outlines of this study are:

- Wave power of flow generated sound is related to the speed of flow.
- As the flow speed increases the wave power increases too.
- Flow speed can be estimated by the flow generated sound.
- Wave power is not changing linearly with velocity and the correlation between these two is mentioned in the text.

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