Applied Acoustics 117 (2017) 61–65

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Effect of the aerodynamic force modeling on the tonal noise prediction model for axial fan: Sensitivity and uncertainty analysis

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ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form 7 October 2016
Accepted 18 October 2016
Available online 3 November 2016

Keywords:
Axial fan
Tonal noise
Sensitivity and uncertainty analysis

ABSTRACT

The far-field acoustic pressure emitted by the unsteady rotating force acting by the fan on the fluid is computed using a tonal noise model prediction. Generally, the usefulness of any model depends in part on the accuracy and reliability of its output. Yet, because all models are imperfect abstractions of physical reality, and because precise input data are rarely if ever available, all output values are subject to imprecision. In this paper, the accuracy of the used tonal noise model prediction is easily influenced by the way in which the unsteady rotating force was modeled. To reach a good correlation between the numerical and experimental results, sensitivity and uncertainty analysis are conducted on the used model. The first one consists firstly on assigning to each model input the Sobol index. Then, according to the obtained index value, the most influential input is revealed. The second one leads to the assessment of uncertainties propagation through the model using the Monte Carlo simulation. Finally, the results from both analyses are presented and discussed.

1. Introduction

In order to better understand physical phenomena and to simulate an experience which is costly or hard to construct, mathematical models describing these phenomena are used. For complicated physical problems, a large number of input parameters is required and the corresponding model becomes more complex. To improve the model accuracy compared to the experimental results, the effect of the inputs on the model outputs should be investigated. For this, two kinds of analysis which are the sensitivity analysis and the uncertainty analysis can be used. The first one allows studying how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input [1]. As a result, an index reflecting the importance of an input on the model output is assigned to each input parameter [2]. The second analysis describes the propagation of a given uncertainty through the model [3]. The axial fan is one of elements mostly used in many industrial applications (ventilation systems, engine cooling fans, etc.). Therefore, there is a need for manufacturers to design improved low-noise axial fans. In a previous work [4], a simple model for predicting the tonal noise of an axial flow fan was developed. The model results showed that the axial fan has dipolar directivity. By comparing the computed and the experimental acoustic directivity, a good agreement was obtained except in some angular positions. The main cause of this exception was not investigated. This paper is a continuity of the previous work [4] and leads to explain the slight shift observed between the model and the experience in estimating the tonal noise of an axial fan. To reach this goal, sensitivity and uncertainty analysis are used to determine the most influential inputs on acoustic pressure emitted by the axial fan. The first analysis is based on the estimation of the Sobol index [5]. The second one uses the Monte Carlo technique to study the propagation of inputs errors on the axial fan acoustic directivity prediction [6]. The outlines of this paper are as follow: in Section 2, a recall on the tonal noise model prediction of an axial fan is presented. Then, the sensitivity and uncertainty analysis carried on this model are detailed in Section 3. Finally, numerical results from each analysis are presented and discussed in Section 4.

2. Tonal noise model prediction of axial fan

This section presents the numerical model under investigation used for axial fan tonal noise prediction. This tonal noise is due to a distribution of aerodynamic forces applied on the fan blades surface [4]. These forces are modeled with an equivalent punctual force called the aerodynamic force applied on the aerodynamic center of the blade [7]. The acoustic pressure measured at a far-field free space is obtained from the following equation [8]:

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http://dx.doi.org/10.1016/j.apacoust.2016.10.017
0003-682X/

$$p(t) = -\frac{1}{4\pi}\iint_S \frac{r_i}{c_0 D_{op} r^2}\frac{\partial}{\partial\tau}\left(\frac{F_i}{D_{op}}\right)\mathrm{d}S \quad (1)$$

With t and τ are respectively the time relative to the observer and to the source, F_i the component of the unsteady rotating force acting by the fan blades on the fluid, r_i the component of the source-observer vector $\vec{r}$ and D_{op} is the Doppler factor.

The equation relating the sources (Fourier coefficients of the aerodynamic force) to the measures (Fourier coefficients of the acoustic pressure) in the case of far-field free space is given as follows [9,4]:

$$P_s = \frac{is\omega}{4\pi c_0 r_0} e^{is\omega\frac{r_0}{c_0}} \sum_{q=-\infty}^{+\infty} (-i)^q J_q\left(s\omega\frac{r_s}{c_0}\sin\theta\right) e^{iq\varphi}\left(T_{s-q}\cos\theta + \frac{qc_0}{s\omega r_s} D_{s-q}\right) \quad (2)$$

P_s is the s^{th} Fourier coefficient of the acoustic pressure at an observation point in the free space due to a singular aerodynamic force concentrated at fan blade. T_{s-q} and D_{s-q} are the $(s-q)^{\text{th}}$ Fourier coefficient of respectively the thrust and drag forces. If the fan is composed by B blades, the sth Fourier coefficient of the acoustic pressure is obtained by the superposition of the sound produced by the B forces.

The developed direct model was validated in earlier study with directivity experiences conducted in anechoic room [4]. The acoustic pressures from seven blade axial fan were measured at equally distributed positions on a circle which is centered on the fan. A good agreement between the numerical and experimental directivities results was obtained on the amplitudes as well as on the shape of a dipolar source. Nevertheless, a slight shift was observed at some angular positions. The objective of the following sections is to find the main cause of this disagreement using the sensitivity and uncertainty analysis.

3. Statistics techniques for uncertainty and sensitivity analysis

3.1. Sensitivity analysis: Sobol index

The model input vector is denoted $X = \{x_1, x_2, \ldots, x_n\} \in \mathbb{R}^n$. The scalar $Y \in \mathbb{R}$ representing the only output of the model $f(\cdot)$:

$$Y = f(X) \quad (3)$$

In the probabilistic setting, X is a random vector defined by a probability distribution and Y is a random variable. In the following, the inputs x_i $(i = 1 \ldots n)$ are mutually independent. The sensitivity analysis allows studying the influence of each input x_i on the variation of the output Y. Therefore, a sensitivity index is firstly assigned to each model input and then the importance and the contribution of each parameter on the model output variation are quantified. The choice of the adequate technique for indices computation depends on the model complexity. The first approach to sensitivity analysis is a deterministic approach known as the local approach. It consists on calculating or estimating the partial derivatives of the modal at a specific point [10]. To overcome the limitations of local approach (linearity and normally assumptions, local variation), a global sensitivity analysis has been developed which considers the whole variation range of the inputs [1]. In the case of non-linear and non-monotonic model, the decomposition of the output variance can be used for sensitivity analysis. This technique is used by Sobol [11] and Jacques [5] to quantify the sensitivity of the output Y to the input x_i. The Sobol sensitivity indices S_i are defined as follows:

$$S_i = \frac{V[\mathbb{E}(Y|x_i)]}{V(Y)} \quad (4)$$

$V[\mathbb{E}(Y|x_i)]$ is the variance of the conditional expectation of Y with respect to x_i and $V(Y)$ is the total variance of the output Y.

3.2. Uncertainty analysis: the Monte Carlo method

In order to study the propagation of uncertainties through the model, uncertainty analysis is used. A random distribution (uniform, Gaussian) is firstly applied on one or all model input and then their impact on the model output is investigated. As a result of this analysis, precautions to be taken into account when carrying out simulation are established.

The computing steps for the Monte Carlo simulation used in this analysis are regrouped in the diagram illustrated by Fig. 1 [12]. The first step consists on defining the probability distribution for each input. Then, a set of random inputs x_i are chosen following the predefined distribution. After that, the algorithm is executed for each value of the input to generate a set of outputs. Finally, the obtained outputs are regrouped and analyzed.

4. Results and discussion

4.1. Studied case and parameters

The studied fan, described by Fig. 2(a), is a seven blade cooling computer fan similar to the one used in [4]. As mentioned before, the accuracy in computing the acoustic pressure emitted by the fan depends on the modeling of the aerodynamic force. In order to evaluate this, five parameters of the corresponding force must be taken into account (Fig. 2(b)): x_1 and x_2 represent respectively the width and the amplitude of the thrust force first fall corresponding to the first or the second arm support of the electric motor. x_3 and x_4 are respectively the width and the amplitude of the thrust force third fall corresponding to the arm containing the electric motor wire $(x_1 < x_3)$. The parameter x_5 is the total amplitude of the thrust force computed using the following equation:

$$x_5 = \frac{30P_m}{Br_s\pi N_r} \quad (5)$$

P_m is the fan motor power, B the blades number, r_s the source radius and N_r the fan speed.

4.2. Sensitivity analysis results

The first value for each input parameter is found by a genetic algorithm using a reference experience [4] and the average value is taken (Table 1). Then, a variation of ±5% is applied on each input according to the uniform law (Fig. 3). After that, the Sobol indices

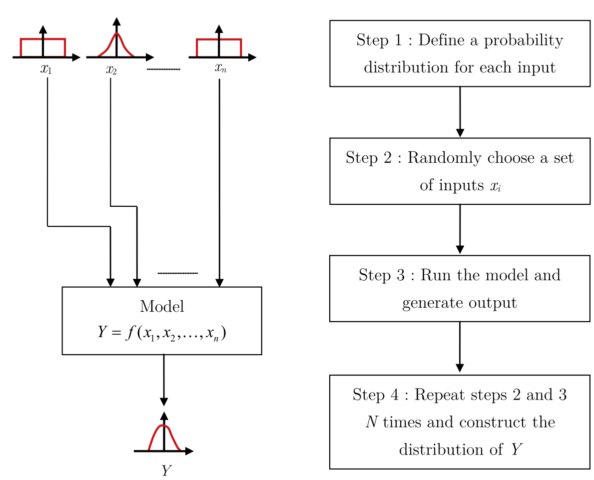

Fig. 1. Uncertainty analysis algorithm using the Monte Carlo method.