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The fuzzy two-load method for measurement of ducted one-port source characteristics

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ABSTRACT

Knowledge of source characteristics is important for the calculation of sound pressure level and insertion loss of a silencer in sourced ducts. Measurement is usually the only feasible approach for the determination of source characteristics. The present paper is concerned with the measurement methods based on the Helmholtz-Thévenin equivalent of ducted one-port plane wave sources. Existing methods are classified as crisp and over-determined methods. In the crisp methods, the measured data are just sufficient for unique characterization of the source. This calls for two loads if their phase relative to the source is known, otherwise three loads are required. Over-determined methods use more number of loads than the crisp methods and are motivated for possible minimization of variations due to measurement errors. The point estimates for the source parameters are, however, still subject to some uncertainty, but estimation of confidence intervals is not feasible because the loads do not constitute a probability sample. The present paper proposes an approach which can yield the source characteristics in intervals from auto-power spectral density measurements with only two loads. The method is based on a novel Apollonian circle formulation. It is called the fuzzy two-load method, because uncertainty inherent to measurements is modelled by fuzzification of a characteristic parameter of the Apollonian circle of two loads. Fuzzy number transformations leading to the source pressure strength, sound pressure level and insertion loss interval predictions are discussed in depth. The paper includes an application showing the working features of the fuzzy two-load method.

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1. Introduction

Sources of duct-borne sound in fluid machinery are various. In general, they are associated with effects that apply a non-steady compressive strain to the fluid contained in the duct. Typical effects include: Moving solid surfaces, stationary surfaces obstructing path of fluid flow, non-steady mass injection, non-steady heating of the fluid, vortex generation and flow momentum fluctuations [1]. True fluid dynamic characterization of these mechanisms is difficult and a black-box approach [2] is preferred in most engineering applications.

In the present paper, we consider the sourced-duct systems where the acoustic propagation can be assumed to be linear and actual source mechanisms can be characterized by an equivalent source located at a convenient section of the system, which may be far downstream of the actual source region. The mathematical basis for the black-box representation of this

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situation is provided by the classical Helmholtz-Thévenin theorem [3]. This states that, any linear two-terminal electrical network is equivalent to a voltage source in series with the network in which all sources are set to zero. This theorem is usually applied to duct-acoustic networks by invoking the voltage-acoustic pressure analogy and gives the well-known frequency domain relations [4]

$$p_S(f) = Z_S(f)v_1'(f) + p_1'(f) \tag{1}$$

$$p_1'(f) = Z_1(f)v_1'(f) \tag{2}$$

where $p_1'(f)$ and $v_1'(f)$ denote, respectively, the acoustic pressure and particle velocity at the equivalent source plane, which is connoted by subscript '1' and where only plane waves are assumed to propagate, $Z_1(f)$ denotes the load impedance, and f denotes the frequency, the dependence on which is usually not shown explicitly in the following when obvious from the context of the discussion. Thus, the Helmholtz-Thévenin equivalent defines an active black box which is characterized by two frequency-domain parameters $p_S(f)$ and $Z_S(f)$, which are called the source pressure strength and the source impedance, respectively. This type of active black box with two terminals is usually called one-port source.

Much of the contemporary work, including the present analysis, on the measurement of equivalent one-port source characteristics in fluid machinery revolves round the solution of Eqs. (1) and (2), given Z_1 and the corresponding p_1' for a sufficient number of cases.[1] The existing methods can be classified in several ways [4]. Here, we prefer to look at them in two groups, as crisp and over-determined methods, as this provides an appropriate background for the fuzzy two-load method [6], the theory of which is expounded in this paper for the first time.

A method which is based on unique (deterministic) solution of Eqs. (1) and (2) for p_S and Z_S is called a crisp method. Interestingly, this definition is not quite obvious at once from the existing literature on the subject. A re-visit to the fundamentals of the existing methods clarifies that only the two-load and three-load methods are theoretically crisp (Appendix A). Then, a method which employs more loads than that needed for a crisp method is called an over-determined method. Such methods are essentially model fitting techniques and usually involve error minimization with respect to the Helmholtz-Thévenin equivalent in the least squares sense. Considerable progress is achieved recently in optimization of load combinations [7], detecting the consistency of the linear source model [8] and testing non-linearity inherent to the measured system [9]. However, the point (or average) estimates provided by an over-determined method for the equivalent source parameters carry no information of how closely the true values of the parameters are estimated. This information is best specified by estimating intervals that include the point estimates. In probability sampling, such intervals are calculated routinely and are known as confidence intervals. But, in over-determined methods, the loads do not constitute a probability sample and, therefore, calculation of such confidence intervals is not feasible.

In this paper, the problem of using Eqs. (1) and (2) for measurement of p_S and Z_S is approached as an interval analysis problem. More specifically, we aim to supplement the crisp (unique) solution of Eqs. (1) and (2) by upper and lower bounds. The proposed solution of this problem is based on the observation that, the crisp solution of Eqs. (1) and (2) for the source impedance with two loads lies on the Apollonian circle [10] of these loads. The uncertainty due to measurement errors is then instilled into the formulation by fuzzification [11] of the characteristic ratio of this Apollonian circle and, hence, the name the fuzzy two-load method.

This approach can be implemented by scanning a sufficiently large number of points on appropriate Apollonian circles numerically [6], but in eventual sound pressure level calculations, which constitute the main premise for source characterization, it is also necessary to scan the same points. Thus, the computational overhead can be high, which is not desirable from practical point of view. In the present paper, the numerical scanning approach is discussed only briefly for future reference; the analysis is largely concerned with the development of analytical a posteriori inequalities that eliminate the need for numerical scanning.

The elements of the fuzzy two-load method are presented in two sections: Section 2.1 introduces the crisp topological properties of the crisp Apollonian circle of two loads and derives a posteriori inequalities for the source pressure strength; Section 2.2 describes the fuzzification and defuzzification processes and derives a posteriori inequalities which yield the source pressure strength as a fuzzy set, the core of which is given by the crisp interval derived in Section 2.1. The condition under which this fuzzy set becomes a fuzzy number is important for the working of the fuzzy two-load method and is discussed in depth. In Section 2.3, we describe the use of the source characterization provided by the fuzzy two-load method in sound pressure level predictions. The paper also includes discussions on insertion loss calculation (Section 2.4) and over-determined implementation of the fuzzy two-load method (Section 2.5). Finally, Section 3 presents an application which illustrates the working features of the fuzzy two-load method. Some basic concepts and jargon of the theory of fuzzy sets, which are necessarily invoked in the analysis, are summarized in Appendix B for convenience.

[1] Helmholtz-Thévenin theorem also hints at how Z_S and p_S can be measured directly without using these equations. To get Z_S: Switch-off the source and measure the driving-point impedance as seen from the equivalent source plane. This is known as the external source method [4,5]. To get p_S: Simulate the acoustic equivalent of the electrical short-circuit condition at the equivalent source plane and measure the prevailing acoustic pressure. These direct implications are out of scope of the present paper, as they raise some conceptual and practical issues which need to be given separate consideration for applications on fluid machinery sources.

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