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Fan-independent air balancing method based on computation model of air duct system

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ABSTRACT

This paper presents a novel fan-independent air balancing method based on computational model of air duct system. The method involves five procedures: 1) model formulation, 2) data acquisition, 3) parameter identification, 4) balancing calculation and 5) adjusting implementation. The duct network model consists of models of components like fans and conduits and assembles them by the conservation laws. Instead of using parametric model with constant parameters, the fan is re-modeled as a variable pressure source. The supply pressure near the fan outlet is measured in addition to the conventional measurements of pressures and airflows at the terminals. A model identification algorithm is designed to estimate both duct model parameters and fan pressure. The optimal damper positions corresponding to the desired airflow distribution are computed by the obtained model. In this way, damper adjusting strategies are generated by the computing results where a novel indicator is introduced to handle variations of fan pressure. The performance of this method is validated in a simulated duct network system with eight terminals. The results show that modeling fan as variable pressure source can achieve balancing accuracy within 2% error. Comparing to the previous method base on parametric fan model, this method has advantages of better accuracy, stronger robustness and higher efficiency under various conditions of fan characteristics and disturbances.

1. Introduction

In modern buildings, heating, ventilation and air conditioning (HVAC) systems play the most critical roles for satisfying ever-increasing demand of high indoor air quality and thermal comfort. For this purpose, the energy consumption for space heating, cooling and ventilation can reach as high as 50% of annual energy consumption of a building in U.S. [1], and this portion reaches even higher (60% for cooling, 10% for ventilation) in Singapore [2]. The ventilation is the major means to reduce air contaminant concentration. Inadequacy of ventilation is one of the factors causing the occupants suffering from sick building syndrome [3,4]. To provide ventilation, the HVAC systems firstly process the outdoor air in centralized air handling units located at plant room and then distribute it to multiple terminals via ducts. Although the overall ventilation rate appears adequate, ventilation in different terminals may still be unevenly distributed. Therefore, the air balancing to proportion the airflow rates as designed in all terminals of the duct system is crucial for the comfortable indoor environment. Furthermore, the over-ventilation in some terminals is a waste of energy and should be avoided to improve energy efficiency. Therefore, balancing the amount of air delivered to each terminal is beneficial to both indoor air quality and energy efficiency. The ASHRAE standard suggests regular balancing for all constant/variable air volume (CAV/VAV), induction, return air and even toilet and kitchen exhaust systems [5].

The air balancing is related with duct sizing [6–9], airflow measurements [10] and testing, adjusting and balancing (TAB) [5]. The TAB is the most important means both accepted in standard [11] and applied by most HVAC contractors. It can be applied in CAV, VAV, return and exhaust systems. The biggest difficulty of air balancing is the complex interaction between terminals. Traditional TAB methods are proportional method and stepwise method. These methods adjust dampers in an iterative manner according to simple rules of thumb, which are inaccurate, time-consuming and costly due to their inefficient trail-and-error nature. The results largely depend on engineers' experiences. In fact, Okochi et al. [12] suggested that balancing and distribution of airflow in VAV system can

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Nomenclature

ΔP	pressure drop along duct (Pa)
q	airflow rate in duct (m^3/s)
b	duct resistance (kg/m^7)
K	damper parameter (kg/m^7)
$\mathbf{A}$	association matrix
N	number of branches
M	number of nodes
$\mathbf{P}$	vector of nodal pressures (Pa)
$\mathbf{q}$	vector of branch flow rates (m^3/s)
$\Delta\mathbf{P}$	pressure differences across branches (Pa)
n_T	number of terminals or dampers
m	number of measurements per terminal
$\mathbf{X}$	state vector of the duct system
$\widehat{P}_i$	measured pressure of record i (Pa)
$\widehat{P}_i$	measured fan outlet pressure of record i (Pa)
$\widehat{q}_i$	measured airflow rate of record i (m^3/s)
$\mathbf{C}_i$	observation matrix of record i
$\widehat{\mathbf{q}}$	normalized airflow rate (Dimensionless)
k_0	index of idle damper
$\widehat{\mathbf{q}}_t$	vector of the normalized designed airflow rates
$\widehat{\mathbf{q}}_0$	vector of normalized terminal airflow rates on fully open condition
$\mathbf{B}$	target matrix
$\mathbf{K}^*$	vector of optimal damper parameter at balance (kg/m^7)
$\tilde{\mathbf{q}}(i)$	transient expected airflow rate on step i of damper adjustments (m^3/s)
$r(i)$	transient indicator on step i of damper adjustments

Greek

θ	damper position (Dimensionless)
θ^*	optimal damper position at balance (Dimensionless)
$\boldsymbol{\beta}$	vector of dominant parameters
$\widehat{\boldsymbol{\beta}}$	posteriori estimation of dominant parameters
σ_q	sensor uncertainty of airflow rate measurement (m^3/s)
σ_P	sensor uncertainty of pressure measurement (Pa)

be considered as one of the main challenging area of research concerning VAV system control. To overcome the low efficiency of the existing iterative methods, the idea of developing non-iterative TAB methods is gradually accepted in this area. Among the limited research works, two categories of approaches become clear: the procedure-oriented approach and model-based approach. The procedure-oriented approach utilizes the properties of duct system and devices to compensate the complex interaction, and thus adjusts dampers straightforwardly to achieve air balancing. Each procedure-oriented method defines a specific sequence of damper adjustments, and it must be completely performed to achieve balancing for all terminals. The model-based approach analyzes the duct system by developing mathematical models and optimizes the damper adjustments. In particular, the grey-box model is usually adopted because it benefits from the qualities of both physical models and data-driven models [13], and it is widely applied in control of chiller [14,15], AHU [16] and active chilled beam terminals [17].

Pedranzini et al. [18] presented the first procedure-oriented method, the progressive flow method. This method is non-iterative to improve efficiency of air balancing. It is estimated that 57%–67% fewer adjustments are required compared with the proportional method. In order to decouple the interactions between adjusted and un-adjusted terminals, an additional flow rate controller for continuous fan speed control is adopted. Later, Tamminen et al. [19] proposed a simpler method based on fan law to estimate the total airflow rate. During the adjusting process, the fan static pressure keeps constant while the total airflow rate is adjusted by variable speed drive to meet the desired airflow rates in each terminal. Simulations and experimental results in a small-scale ventilation duct system have shown adequate accuracy (within 5% tolerance).

Small et al. [20] proposed a model-based method for TAB by modeling the duct network based on quadratic fan curve approximation and quadratic duct pressure drop. Parameters in the model are identified by using the data which are acquired by measuring airflow in two conditions: all dampers are fully open at first, and then one damper is closed. Based on the identified model, damper positions to achieve balanced air distribution are calculated. Due to the high sensitivity, the relative errors of sensors are significant comparing to the change of airflow rates, which affect the balancing accuracy. Chen et al. [21] proposed a different measuring procedure to improve the quality of measured data while making the procedure more convenient. The identification method is based on maximum a posteriori to reduce sensor uncertainty and improve accuracy. The balancing accuracy achieves 4.7%, which is significant better than the 10% tolerance according to ASHRAE's standards [22]. However, the computational cost for solving the implicit Darcy-Weisbach equation is high.

The performance curves of fans, which depend on type of fan blades, driving motors and housing design, are generally difficult to be modeled. Although fan law express the homology between two performance curves of geometrically similar series of fans [23], the physical model of fan performance that quantify pressures in terms of airflow rate has not yet established. Current available fan curve models like quadratic model are unable to describe the performance curve in the whole range. In additional, when retrofitting existing duct system, the original performance curve of fan may be inaccessible, and thus it is difficult to obtain the model of fan. Furthermore, disturbances from upstream flow of the duct system under balancing could also affect the pressures and flowrates. Therefore, it is of great significant to develop suitable methods to balance duct system without known the pressure-flowrate relationship. For this reason, the author proposes a fan-independent method for TAB based on grey model of duct network. The advantages of the proposed method are three folds: 1) improving modeling accuracy, 2) improving robustness against disturbances from fans, and 3) improving efficiency of balancing. The fan-independent method consists of model formulation, measurement acquisition, parameter identification, balancing calculation, and adjusting implementation. The conventional parametric fan model is replaced by a variable pressure source to adapt to arbitrary fan characteristics. For each damper, at least two measurements in different damper positions are taken. Each set of data is a triple of measurements taken at the terminal outlet, upstream side of the damper and the fan outlet. Model identification algorithm estimates both the duct model parameters and the fan pressures simultaneously. To handle variations of fan pressure, a new indicator for the damper adjustments is introduced. By using this method, the balancing error can be further reduced as well as the