AN-04-3-2

Total Energy Consumption Model of Fan Subsystem Suitable for Continuous Commissioning

Fulin Wang

Harunori Yoshida, Ph.D.
Member ASHRAE

Masato Miyata

ABSTRACT

This paper describes a newly developed total energy consumption model of a fan subsystem, which consists of fan, driveline, motor, and variable-speed drive. How to use this model for automated continuous commissioning is explained and verified using an experimental study. This model can accurately simulate the total energy consumption of a fan subsystem, which can be easily measured. Therefore, this model is useful for the automated continuous commissioning of a fan subsystem during operation. The simulation results were verified using measured data in a real variable-air-volume system. The average difference between the simulated and measured data is 5.1%, which is accurate enough from an automated continuous commissioning point of view to monitor the operation of a fan subsystem and detect faults during operation. An experiment demonstrated that loose fan belts can be detected and the results are discussed as an example showing that the model can successfully detect this fault.

INTRODUCTION

Building commissioning is the process of ensuring that building systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent (ASHRAE 1996). The awareness that commissioning is a viable method to help ensure buildings and their energy conservation measures (ECMs) meet design intent has been gradually growing since the 1980s. Some analyses of the data from the buildings participating in an energy conservation program revealed that many installed energy efficiency measures were not performing as expected (BPA 1992). The main reason is that the installed ECMs had not been properly commissioned. Building commissioning begins with the program phase and continues through the design phase, construction phase, acceptance phase, and post-acceptance phase (ASHRAE 1996). Post-acceptance phase commissioning is to continuously commission the building systems to make them always run efficiently during their whole life cycle.

For the purpose of automatically and continuously commissioning fan subsystems using simulation analysis during the operation phase, currently available fan simulation models were checked to determine whether or not these models are suitable for continuous commissioning. Model validity checking showed that no fan model can give simulation results that match the experimental measured data quite well. Therefore, a new total energy consumption model of a fan subsystem was developed, which is suitable and useful for continuous commissioning. This newly developed model's accuracy and validity for continuous commissioning were verified using experiments.

MODELS

The fan models used by currently available simulation tools can only simulate the performance of a fan itself. There are no models to simulate the performance of other components in a fan subsystem, such as motor, inverter, etc. For example, SIMBAD can simulate a fan's energy consumption using an empirical equation by inputting the real-time and maximum airflow rate and maximum energy consumption (CSTB 2001). HVACSIM+ is able to simulate a fan's energy consumption and a fan's pressure head using airflow rate and fan rotation speed by a series of equations fitted using manufacturer's data (Clark 1985).

Fulin Wang is a Ph.D. candidate, **Harunori Yoshida** is a professor, and **Masato Miyata** is a master's student in the Department of Urban and Environmental Engineering, Kyoto University, Kyoto, Japan.

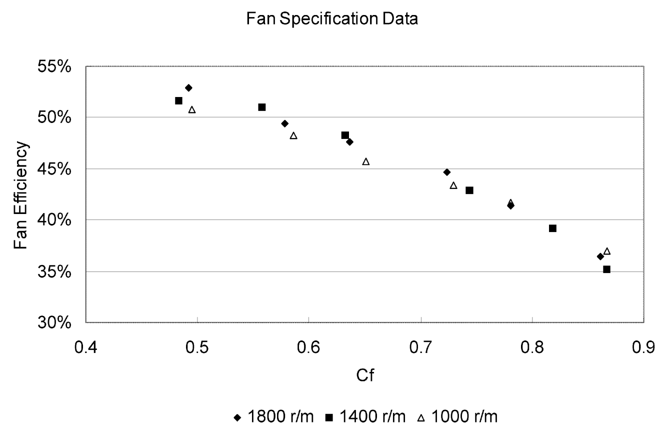

Figure 1 *Fan efficiency vs. dimensionless airflow rate.*

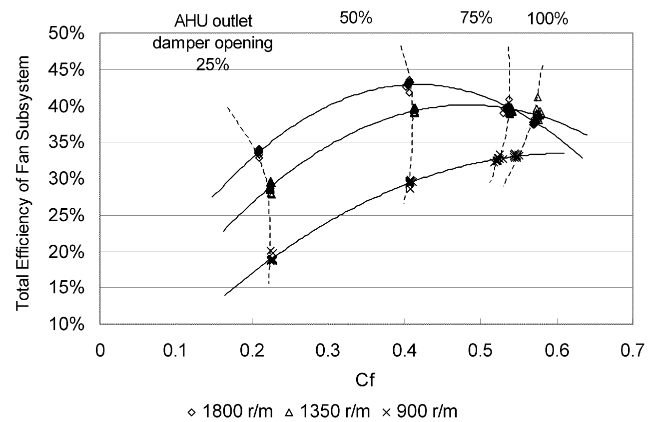

Figure 2 *Total efficiency of fan subsystem vs. Dimensionless airflow rate.*

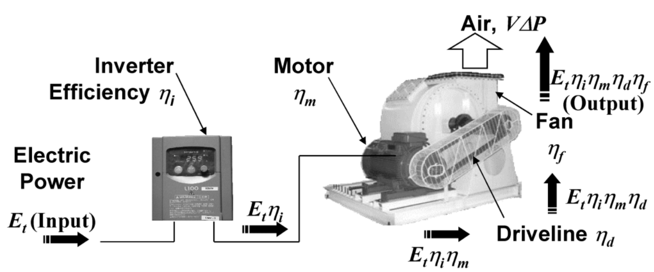

Figure 3 *Components and energy flow of a fan subsystem.*

However, it is difficult to commission a fan using these models because they simulate the energy consumption of a fan itself and this energy consumption, which is termed *fan shaft power*, is difficult to measure. Especially during the operations phase, there is no building energy management system (BEMS) that measures a fan's shaft power; but it is very easy to measure the total power consumed by the fan subsystem, which includes fan, driveline, motor, and variable-speed drive (VSD), using a power meter set at the power input point such as the power switch. If the above-mentioned fan models are used to simulate the total power consumption of a fan subsystem, they will not give acceptable results. For instance, SIMBAD gives an average difference of 50%, and HVACSIM offers an average difference of 48%. Therefore, it is unreasonable to use these fan simulation models for continuous commissioning. Furthermore, the characteristics of total efficiency of a fan subsystem are different from that of the fan itself. A fan's efficiency changes only according to dimensionless air-flow rate C_f. The η- C_f curve shows a uniform shape at different fan rotation speeds, as shown in Figure 1, whereas the total efficiency of a fan subsystem changes according to not only C_f but also fan rotation speed, as shown in Figure 2. Therefore, new total efficiency models of fan subsystems are needed to express the unique characteristics of a fan subsystem. To address this problem, a total energy consumption model was proposed, which takes into account the performance of all the components in a fan subsystem, i.e., fan, driveline, motor, and VSD inverter. The components and energy flow of a fan subsystem are shown in Figure 3. The total energy consumption model is defined by the following equations.

$$E_t = \frac{V\Delta P}{\eta_t} \tag{1}$$

$$\eta_t = \eta_f \eta_d \eta_m \eta_i \tag{2}$$

$$\eta_f = e_0 + e_1 C_f + e_2 C_f^2 + e_3 C_f^3 + e_4 C_f^4 \tag{3}$$

$$\eta_m = m_0 + m_1 L + m_2 L^2 + m_3 L^3 + m_4 L^4 \tag{4}$$

$$\eta_i = i_0 + i_1 L + i_2 L^2 + i_3 L^3 + i_4 L^4 \tag{5}$$

$$L = \frac{V\Delta P}{\eta_f E_r} \tag{6}$$

$$C_f = f_0 + f_1 C_r + f_2 C_r^2 + f_3 C_r^3 + f_4 C_r^4 \tag{7}$$

$$C_r = \frac{\rho V^2}{\Delta P D^4} \tag{8}$$

$$C_f = \frac{V}{ND^3} \tag{9}$$

$$N = \frac{INV}{INV_r} N_r \tag{10}$$

Equation 1 is used to calculate the total energy consumption of a fan subsystem using airflow rate, pressure head, and total efficiency of the fan subsystem. Total efficiency of a fan subsystem is calculated using Equation 2 by multiplying the efficiency of all the components of the fan subsystem, i.e., fan, driveline, motor, and inverter. Equation 3 is used to calculate

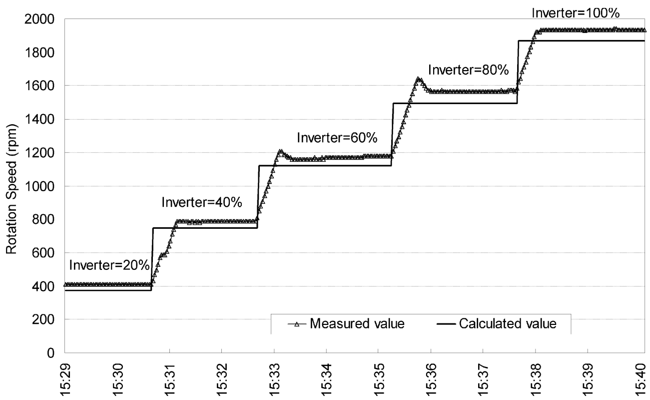

Figure 4 *Comparison of measured and calculated fan rotation speed.*

fan efficiency using a fourth-order function of dimensionless airflow rate. This equation is taken from HVACSIM+ (Clark 1985). Motor and inverter efficiency is calculated using Equations 4 and 5, respectively, which are fourth-order functions of load factor. Load factor is calculated using Equation 6, which is the rate of fan shaft power to rated shaft power.

As discussed below, Equation 7 is used to calculate the dimensionless airflow rate using dimensionless flow resistance. Dimensionless flow resistance is calculated using Equation 8, instead of the method used in HVACSIM+, which uses airflow rate and fan rotation speed as shown in Equation 9. Fan rotation speed is estimated using Equation 10 from rated rotation speed and inverter output frequency.

Fan Efficiency Model

Equation 3 shows a fan efficiency model used in HVAC-SIM+. This fan efficiency model simulates a fan's efficiency using dimensionless airflow rate C_f, which is calculated using airflow rate and fan rotation speed. However, for a gear driven or cog-belt driven fan subsystem, the fan rotation speed can be calculated using inverter output frequency and rated rotation speed, as shown in Equation 10, because no slippage occurs in gear drivelines and cog-belt drivelines. Whereas for a v-belt or band belt driven fan subsystem, the belt slippage makes it inaccurate to calculate the transient fan rotation speed using inverter output frequency and rated rotation speed. Furthermore, most BEMS are not installed with a sensor to measure the fan rotation speed. Therefore, for the purpose of continuous commissioning, other models must be used.

One alternative method is to simulate the fan efficiency using airflow rate and fan pressure head. For this purpose, a new dimensionless variable was proposed, dimensionless airflow resistance coefficient C_r, as shown in Equation 8. Using C_r and Equation 7 to calculate C_f, fan efficiency, can be calculated using C_f and Equation 3.

Another method is to estimate fan rotation speed using inverter output frequency, as shown in Equation 10. The accuracy that this estimation could achieve was checked by comparing the measured rotation speeds with estimated ones. The average difference between the measured and estimated rotation speed is 2.2% and the maximum difference is 9.0%, as shown in Figure 4, when inverter output frequency gradually changed from 20% to 100% of rated frequency, 50 Hz. The accuracies of these three fan efficiency simulation methods were compared to determine which one is most suitable for continuous commissioning. The input variables to the three simulation methods are as follows.

- Airflow rate and head pressure
- Airflow rate and measured fan rotation speed
- Airflow rate and calculated fan rotation speed

The average differences between the measured total efficiency of fan subsystem and simulated total efficiency given by these three methods are 5.1%, 6.1%, and 6.5%, respectively. The simulation model using airflow rate and head pressure gave the most accurate simulation results. The simulation accuracy using measured fan rotation speed is 0.4% higher than using calculated fan rotation speed. So it is acceptable to simulate a fan's efficiency using calculated fan rotation speeds instead of measured ones when head pressure is unavailable.

Driveline Efficiency

The newly installed driveline's efficiency can be used as a performance target value during the continuous commissioning phase because the driveline efficiency changes due to aging. So as a driveline's efficiency decreases because of aging, the real total efficiency of a fan subsystem will be lower than the total efficiency simulated using the newly installed driveline's efficiency. Therefore, a newly installed driveline's efficiency can be used in the fan subsystem simulation to help detect the fault of belt aging and is useful for continuous commissioning. The recommended efficiency value for a newly installed V-belt is 95% and for a newly installed cogged or synchronous belt efficiency it is 98% (OIT 2000).

Motor Efficiency

Motor efficiency changes according to two variables, electric frequency and load factor, as shown in Figure 5. Load factor is the percentage of transient motor power output to rated power output. If fan belt efficiency is assumed to be constant at various loads and rated motor output is equal to rated fan power input, the load factor equals the transient fan power input divided by rated fan power input.

For VSD-driven motors in a VAV system, the electric frequency input to the motor is not an independent variable. It is determined according to demand airflow rate and pressure, which determine the load on the motor. Therefore, required motor input frequencies are related to load factors. The relationship between load factor L and required frequency F can

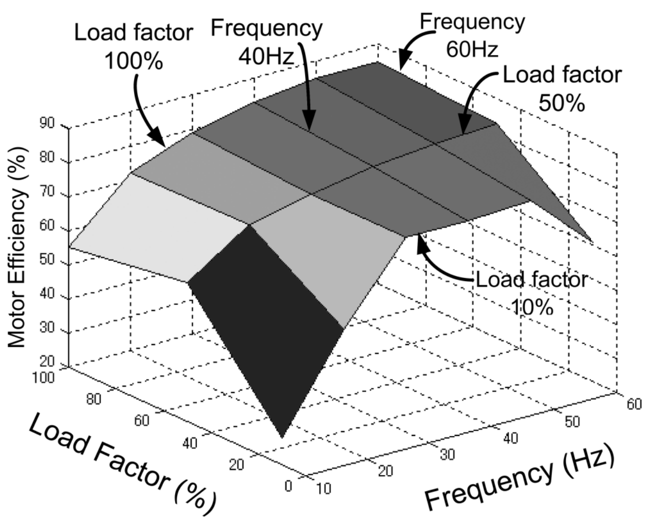

Figure 5 *Motor efficiency vs. load factor and frequency.*

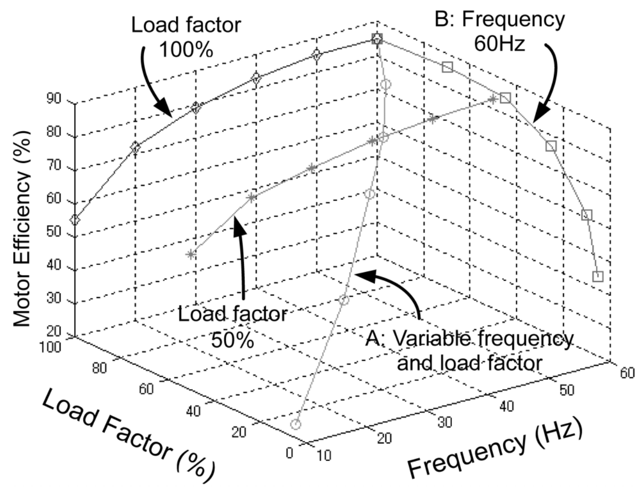

Figure 6 *VAV system motor efficiency vs. load factor and frequency.*

be derived, as shown in the Equations 11 to 13. From Equation 13 it can be found that the required electric frequency has one definite value corresponding to one load factor value. Therefore, load factor is the single independent variable that can influence the motor efficiency. So for a VSD-driven motor in a VAV system, the relationship of motor efficiency and frequency and load factor is not a three-dimensional surface, but three-dimensional curves, as shown in Figure 6.

In order to simulate the motor efficiency accurately, Equation 4 needs to be fitted using the data with the relationship of $\eta_m - L - (F / F_r)^3$, as shown by curve A in Figure 6. However, most motor manufacturers only offer data on their motors' efficiency at the conditions of rated frequency and various load factors, as shown by curve B in Figure 6. Therefore, these data have to be used to fit the motor efficiency model. Of course it is not accurate to simulate the motor efficiency in a VAV system using such fitted model. So motor manufacturers should be urged to offer motor efficiency data with the relationship to load factor and frequency at the conditions of $\eta_m - L - (F / F_r)^3$.

$$\frac{V}{V_r} = \frac{N}{N_r} = \frac{F}{F_r} \tag{11}$$

$$\Delta P = SV^2 \tag{12}$$

$$L = \frac{V\Delta P}{V_r \Delta P_r} = \left(\frac{V}{V_r}\right)^3 = \left(\frac{F}{F_r}\right)^3 \tag{13}$$

Inverter Efficiency

Inverters change the electric frequency to make motors' and fans' rotation speed variable. During frequency modulation, inverters consume some energy, which becomes heat and discharges to the local environment. Inverter manufacturers' literature shows the relationship between heat-generating

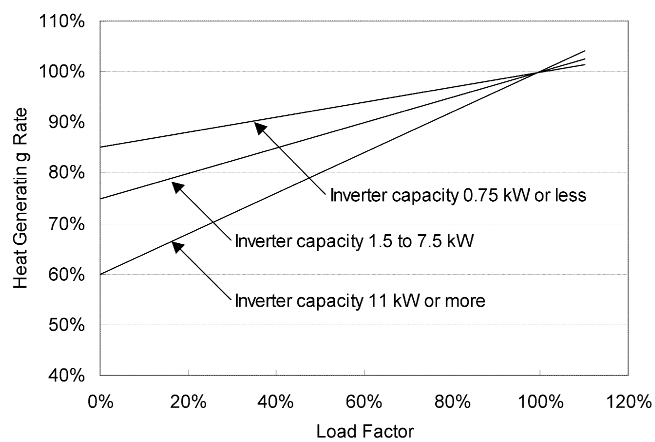

Figure 7 *Inverter heat generating vs. load factor.*

losses and load factors, as shown in Figure 7 (Hitachi 2002). Using these heat-generating rates, the inverter efficiency can be calculated as a function of changing load factor. Using these data of inverter efficiency vs. load factor, the inverter efficiency model can be fitted. The fitted inverter efficiency model can be used to simulate the inverter's efficiency during the operations phase to realize continuous commissioning of a fan subsystem.

EXPERIMENTS

In order to verify the simulation accuracy of this total energy consumption model of fan subsystem and its validity for continuous commissioning, experiments were conducted in August 2002 on a real VAV system in an office building located in Tokyo. In the first experiment, normal fan subsystem operation data were measured to verify the total energy consumption model's accuracy. The second experi-

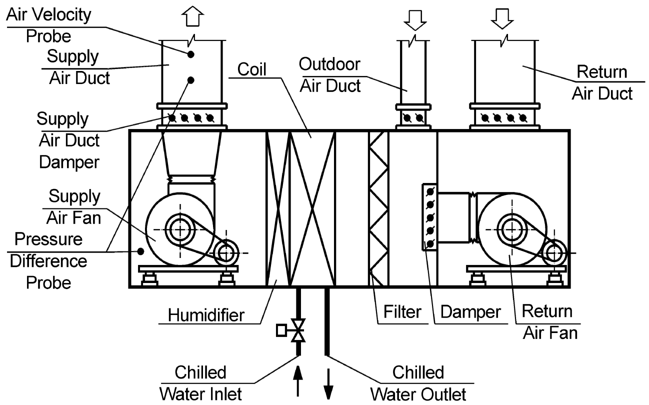

Figure 8 *Measurement points and AHU configuration.*

ment checked whether this total energy consumption model could detect the fault of loose belts. The total electric power consumption, air volume, and head pressure for the supply air fan in an AHU were measured. The measurement points and the configuration of the AHU are shown in Figure 8.

Normal Fan Subsystem

In order to obtain the fan performance data at different load percentages, the inverter output frequency was fixed at 100%, 75%, and 50%. Corresponding to each inverter output frequency, the AHU supply air outlet damper opening was set at 100%, 75%, 50%, and 25%, respectively. The steps of setting these parameters are shown in Figure 9. Fan supply air volume, head pressure, and electric power consumption were measured every one minute and recorded using a data logger. Inverter output frequencies were obtained from the BEMS records.

The simulated total efficiency of the fan subsystem using the total energy consumption model is shown in Figure 10 compared with the measured total efficiency of the fan subsystem, as well as the simulated fan efficiency using Equation 3. The average difference between the simulated and measured total efficiency of fan subsystem is 5.1% and the maximum difference is 12.4%. There are two possible reasons that can explain the difference. One is that the belt efficiency is assumed to be constant, but in fact it varies at different fan rotation speeds. The other possible reason is that the motor efficiency model is fitted using the data at conditions of constant frequency and various load factors, whereas the motor actually ran under conditions of variable frequency and load factor. Nevertheless, the 5.1% average simulation difference is accurate enough for applying this total energy consumption model to commission an HVAC project.

Fan Subsystem with Loose Belts

In order to verify whether this total energy consumption model can detect a fault occurring in a fan subsystem, an application case was studied in which the fan belts of a fan

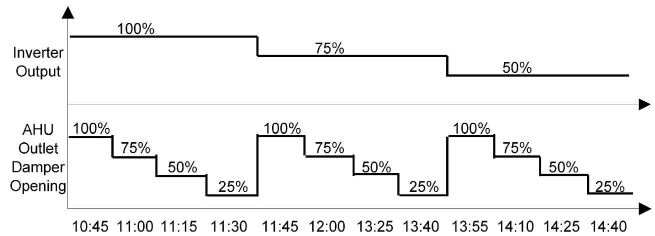

Figure 9 *Experiment step and parameters.*

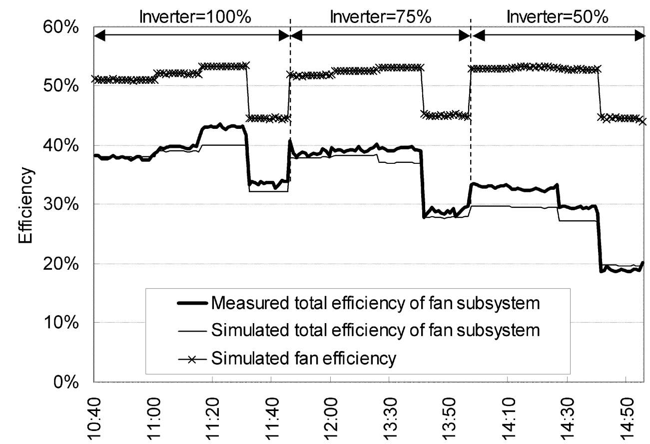

Figure 10 *Simulation accuracy of total energy consumption model.*

subsystem were loosened through replacing the proper size belts with larger ones. Under this condition, the supply air volume, head pressure, and total power consumption of the fan subsystem were measured every minute.

In order to measure the fan performance over a full range, the inverter output frequencies were manually set at 100%, 75%, 50%, and 40% of rated frequency, 50 Hz, instead of being controlled automatically. Corresponding to every inverter output frequency, the VAV box demand/supply airflow rates were manually set at 100%, 75%, 50%, and 30% of the rated airflow rate, which is 4000 m^3/h (2354.3 cfm).

The total energy consumption model was used to simulate the total power consumption of the fan subsystem, which represents the performance of the fan subsystem without faults. The simulated and measured power were compared to determine whether there were some faults that were influencing the operation. In order to make the comparison reasonable and valid for detecting faults, the simulated power consumption was calculated using the same airflow rate and pressure as that of the fan subsystem with loose belts installed. If the same airflow rate and the same pressure are delivered, the power consumed by the fan subsystem with tight belts should be less than that consumed by the fan subsystem with slipping belts. Alternatively stated, a fan subsystem with loose belts would

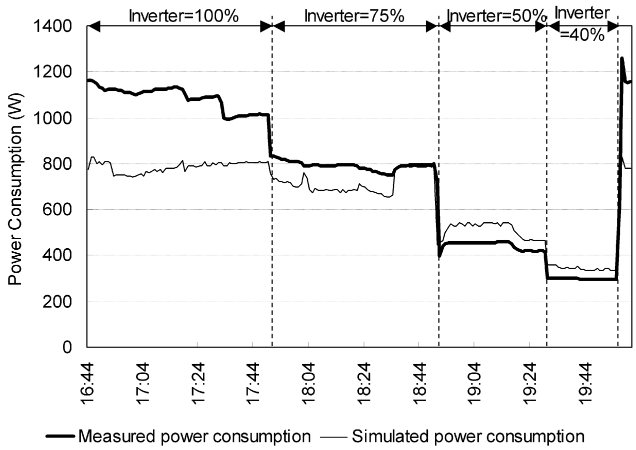

Figure 11 *Total power consumption of a fan subsystem with slipping belts and simulated value with tight belts.*

deliver less airflow and the motor would experience a reduced load, thus reducing the total power consumption of the fan subsystem. This fault condition could be detected using the fan subsystem model.

Figure 11 shows the difference between the simulated total power consumption of the fan subsystem without faults and measured total power consumption of the fan subsystem with loose belts. The average difference between the simulated and measured energy consumption of the fan subsystem is 21.9% and the maximum difference is 61.7%. During high rotation speed, the influence of loose belts is significant and the difference between simulated and measured data is up to 61.7%. During low rotation speed, the influence of loose belts is insignificant and less than the simulation error. These symptoms can be used to develop some rules for fault detection and diagnosis. The average difference of 21.9% shows that the simulation using this total energy consumption model can easily detect this fault. This model is useful for continuous commissioning during the operations phase of a building.

APPLICATION FOR AUTOMATED CONTINUOUS COMMISSIONING

Automated continuous commissioning of a fan subsystem is to continuously monitor the operation of the fan subsystem to determine whether the subsystem is running normally or not and detect and diagnose faults if the subsystem is running abnormally during the operations phase. This total energy consumption model of a fan subsystem can fulfill this purpose using the continuously measured fan supply air volume, fan head pressure or inverter output frequency, and total power consumption of the fan subsystem. Figure 12 shows how to use this total energy consumption model of a fan subsystem for automated continuous commissioning. The

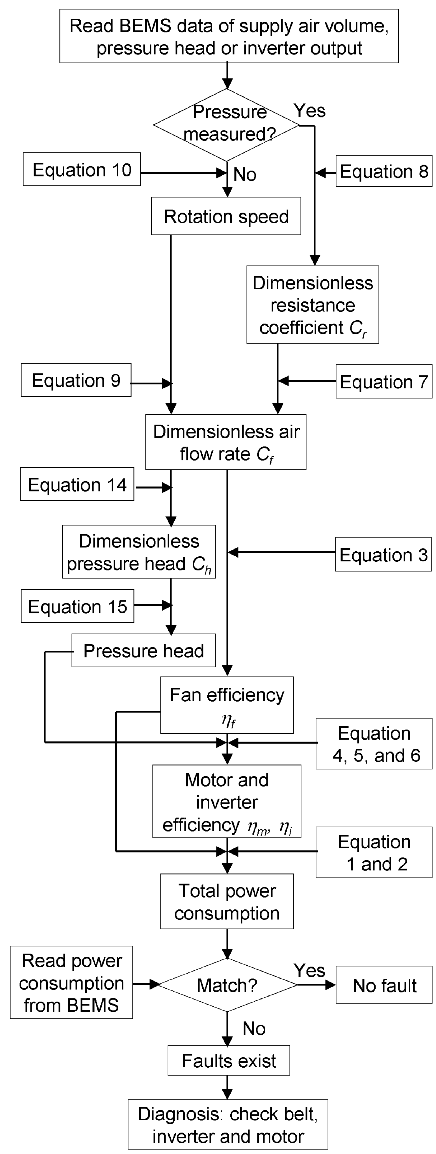

Figure 12 *Flowchart of automated continuous commissioning using total energy consumption model.*

following procedure explains in detail the calculation steps shown in Figure 12.

1. From BEMS collect data that are necessary for simulation, i.e., air volume, inverter output frequency or head pressure, and total energy consumption of a fan subsystem. Sample time interval is recommended to be one minute.
2. If pressure head is measured by BEMS, calculate the fan's dimensionless airflow rate C_f using Equations 8 and 7.
3. If pressure head is not measured, calculate fan rotation speed using Equation 10 and calculate C_f using Equation 9. Calculate head pressure using Equations 14 and 15, which are taken from HVACSIM+.

4. Use Equation 3 and C_f to calculate the fan efficiency η_f.
5. Use Equation 6 and fan efficiency, airflow rate, and pressure head to calculate load factor.
6. Use load factor and Equations 4 and 5 to calculate the motor and inverter efficiency.
7. Use Equations 2 and 1 to calculate the total efficiency and total energy consumption of the fan subsystem.

$$C_h = a_0 + a_1 C_f + a_2 C_f^2 + a_3 C_f^3 + a_4 C_f^4 \tag{14}$$

$$C_h = \frac{\Delta P}{\rho N^2 D^2} \tag{15}$$

By comparing the simulated total power consumption of the fan subsystem with the measured real power consumption, it can be determined whether there are faults that are influencing the performance of the fan subsystem. If the measured data match the simulated data within the error range of the model, it can be concluded that the fan subsystem is running normally. Otherwise if differences between the measured power consumption and simulated power consumption exceed the predetermined threshold, the conclusion can be drawn that some faults are influencing the fan subsystem. We recommend the threshold of the average difference between measured and simulated total power consumption during three hours be 15%. By comparing the symptom with a rule base, the most likely reason for the fault can be given as a diagnosis.

CONCLUSIONS

From the discussion in this paper, the following conclusions can be drawn.

1. This paper proposed a total energy consumption model of a fan subsystem in which motor, inverter, driveline, and fan efficiency are taken into consideration. This total energy consumption model can simulate the total electric power consumption using fan supply air volume and fan head pressure. It avoids the difficulty of measuring a fan's shaft power to verify the performance of the fan during the operations phase. This model is useful for automated continuous commissioning of a fan subsystem through continuously comparing the simulated total electric power consumption and measured data of the fan subsystem because its input variables can be obtained easily and continuously through a BEMS. This model is based on a theoretical analysis of the physical characteristics of fan subsystem components. It is suitable for all fan subsystems consisting of the same components. For a building with several identical fan subsystems, after this model is identified, it can be used to monitor all of them. It can save commissioning work, time, and cost compared to measuring each of the subsystems one by one.
2. A dimensionless variable C_r, which is the dimensionless resistance coefficient of airflow, was proposed to simulate fan efficiency in order to solve the problem of determining the exact rotation speed of a fan subsystem with driveline that might slip, such as v-belt and band belt. VAV systems are increasingly installed with an airflow rate sensor for VAV control, which can be utilized to provide data for this total energy consumption model.
3. The simulation accuracy of this total energy consumption model was verified using a real VAV system. The average difference between the simulated and the measured total electric power consumption of the VAV system is 5.1%, which is accurate enough to monitor the operation of fans, drivelines, motors, and inverters during the operation phase and to detect the faults of an energy-inefficient fan subsystem.
4. Application of this total energy consumption model of a fan subsystem for automated continuous commissioning was explained and demonstrated using an experimental study of a real fan subsystem with loose belts. The case study shows that using the model is able to detect a fault. By using the model in a BEMS configured with an appropriate set of rules, the building operator could be given possible reasons for the fault as a diagnostic result.

ACKNOWLEDGMENT

The authors would like to thank Mr. Makoto Tsubaki and Miss Kanako Itou for helping to carry out the experiments. The authors would also like to acknowledge the help of guiding ASHRAE technical committees and the reviewers for spending much time to review the paper and giving beneficial comments and advice.

NOMENCLATURE

a_0, a_1, a_2, a_3, a_4	=	fitted coefficients using fan specification data
C_f	=	dimensionless coefficient of airflow rate
C_h	=	dimensionless coefficient of pressure head
C_r	=	dimensionless coefficient of airflow resistance
D	=	diameter of fan wheel (m)
e_0, e_1, e_2, e_3, ea_4	=	fitted coefficients of fan efficiency equation using fan specification data
f_0, f_1, f_2, f_3, f_4	=	fitted coefficients using fan specification data
E_r	=	rated fan power consumption (W)
E_t	=	total energy consumption of fan subsystem (W)
F	=	required electric frequency (Hz)
F_r	=	rated motor's electric frequency (Hz)
i_0, i_1, i_2, i_3, i_4	=	fitted coefficients of inverter efficiency equation using inverter specification data
INV	=	invert output frequency (Hz)
$INVr$	=	rated invert output frequency (Hz)
L	=	load factor
m_0, m_1, m_2, m_3, m_4	=	fitted coefficients of motor efficiency equation using motor specification data

N = fan rotation speed (r/s)

N_r = rated fan rotation speed (r/s)

ΔP = fan pressure head (Pa)

S = airflow resistance coefficient (pa/(m^3/s)^2)

V = fan supply air volume flow rate (m^3/s)

η_d = driveline efficiency

η_f = fan efficiency

η_i = inverter efficiency

η_m = motor efficiency

η_t = total efficiency of fan subsystem

ρ = air density (kg/m^3)

REFERENCES

ASHRAE. 1996. *ASHRAE Guideline 1-1996*, *The HVAC Commissioning Process.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

BPA. 1992. *Building Commissioning Guidelines,* Second Edition. Portland: The Bonneville Power Administration, U.S. Department of Energy.

Clark, R.D. 1985. *HVACSIM+ Building Systems and Equipment Simulation Program Reference Manual*, NBSIR 84-2996. Gaithersburg, Md.: U.S. Department of Commerce.

CSTB. 2001. *Manual of SIMBAD version 2.0.0*. Batiment: Centre Scientifique et Technique du Batiment.

Hitachi. 2002. *Hitachi Inverter Technical Guidebook*. Tokyo: Hitachi, Ltd.

Mitsubishi. 2002. *Test Report of Induction Motor*. Nagoya: Mitsubishi Electric Corporation.

OIT. 2000. *Replace V-belt With Cogged or Synchronous Belt Drives*. Merrifield: Office of Industrial Technologies, U.S. Department of Energy.