ACCURACY ANALYSIS OF AIR TORQUE POSITION DAMPERS BASED ON BLADE PROFILES AND DAMPER LOCATIONS

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The primary concern of this paper is a single-blade air torque position damper used for the indirect measurement of volumetric airflow rates by measuring the moment of airstream force exerted on the blade and the damper position. The purpose of the paper is to analyze the accuracy of the air velocity measurements and the adequacy of the damper mathematical model on the basis of the blade profile and the damper location in a duct system. The analysis was performed on the basis of the experimentally obtained results. Four different blade profiles (flat, V-groove, symmetrical airfoil and non-symmetrical airfoil blades) were taken into account, as well as three different damper locations in the duct system (at the duct entrance, within the duct, and at the duct exit). Two blade orientations at the duct entrance were examined relative to the direction of airflow (with front and rear mounting flanges). It was determined that the blade profile and particularly the damper location in the duct system affect the measurement accuracy and the adequacy of the damper mathematical model provided the blade angle of attack is less than or equal to 30^o, i.e. within the range of a more open damper.

Key words: *damper, airflow rate, velocity, measurement*

1.Introduction

The primary concern of the research is to examine the ATP (air torque position) damper. The ATP damper is a device used for the indirect measurement of the air velocity (v) by direct measurements of the blade angle of attack (α) and the moment (M) of airstream force exerted on the blade. The ATP damper was designed by Federspiel [1] utilizing design alterations to dampers for airflow regulation in HVAC (heating, ventilating, and air conditioning) systems. In order to increase the sensitivity of airflow measurement, Federspiel has displaced the axis of rotation of the blade from the axis of the blade in longitudinal and transverse directions. He subsequently developed a mathematical model of such dampers on the basis of the irrotational and incompressible flow of air over a single damper blade, fig. 1.

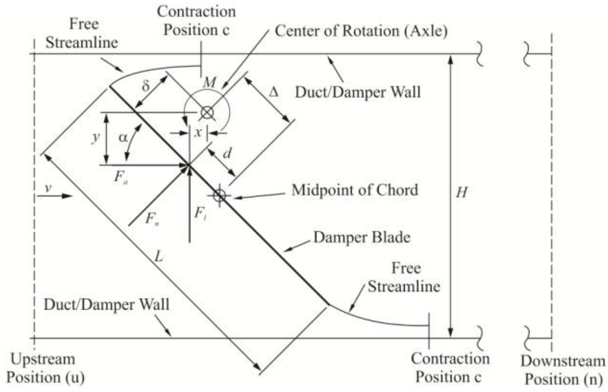

Figure 1. Schematic diagram of a single-blade ATP damper

Federspiel developed the model using the laws of mass, energy and momentum conservation. The model obtained is a correlation between the velocity of air, v [ms^{-1}], directly in front of the damper, the blade angle of attack, α [^{o}], and the moment of airstream force exerted on the blade M [Nm]:

$$v|v| = G^2(\alpha)\frac{2M}{\rho A_u D_h}, \qquad (1)$$

where ρ is the air density [kgm^{-3}], A_u is the cross-sectional area upstream of the damper [m^2], D_h is the hydraulic diameter [m], and G is the correlation function [-]. The density of air, ρ, is in the denominator of the mathematical model as shown in eq. (1). By placing sensors directly in front of the damper blade and measuring the pressure and temperature of air, the density of air can be calculated from the ideal gas equation of state. Consequently, the air velocity can be measured by ATP dampers under different operating conditions. The correlation function derived from eq. (1) is as follows:

$$G(\alpha) = \left(\frac{D_h}{\frac{y}{C_{Q,a}^2} + \frac{x}{C_{Q,l}^2 \cdot tg\alpha}} \right)^{\frac{1}{2}}, \qquad (2)$$

where α is the blade angle of attack [^{o}], x is the axial distance from the axle to the center of pressure [m], y is the lateral distance from the axle to the center of pressure [m], C_{Qa} is the axial flow coefficient [-], and C_{Ql} is the lateral flow coefficient [-].

Federspiel verified the mathematical model (eq. (1)) using a damper with the following characteristics: a square cross section of 0.61x0.61 m^2, a straight duct section following the damper placed at the duct entrance, and four opposed blades (cascading). The difference between the empirically predicted and measured velocity was +/-10% of the measured velocity or +/-5% of the full-scale velocity [2]. The model verified could be used for accurate measurements of the air velocity under different operating conditions. Furthermore, its universal feature is reflected in potential applications to ATP dampers with different cross sections, designs, blade numbers and operations (actions), locations in HVAC systems, etc.

Dampers with non-cascading blades (the number of blades is less than three) are often embedded in HVAC systems. Bikic et al. verified the proposed model (eq. (1)) in the instance of non-cascading ATP dampers. The model of a single flat blade ATP damper was initially verified as a representative of non-cascading dampers [3]. Subsequently, the verification encompassed the damper models with two opposed flat blades, two parallel flat blades, and two flat blades—one of which is a measuring blade and the other is fixed in the horizontal direction [4].

Dampers are installed at three locations in HVAC (heating, ventilating, and air conditioning) systems: at the duct exit with a straight duct section preceding the damper, at the duct entrance with a straight duct section following the damper, and in the duct with a straight duct section both preceding and following the damper. The pressure drop and thus the accuracy of airflow measurement depend on the damper location in the duct system [5], especially regarding dampers used for the indirect measurement of airflow rates by measuring the pressure drop on the damper. In addition to the damper location, the construction also greatly affects the features of dampers installed in HVAC systems [6]. Analogous to dampers used for airflow regulation in HVAC systems, the construction and location (in the duct system) of ATP dampers could exert a significant impact on their features. Therefore, the purpose of this paper is to determine the effects of blade profiles and damper locations in the duct system on the accuracy of airflow measurements and the adequacy of the ATP damper model.

2. Materials and methods

The effects of blade profiles and damper locations in the duct system on the accuracy of airflow measurements and the adequacy of the ATP damper model was experimentally proven. A laboratory facility for testing ATP dampers was constructed in the Laboratory of Fluid Mechanics, at the Faculty of Technical Sciences, the University of Novi Sad, in accordance with the recommendations [7] for testing dampers used for airflow regulation in HVAC systems, fig. 2.

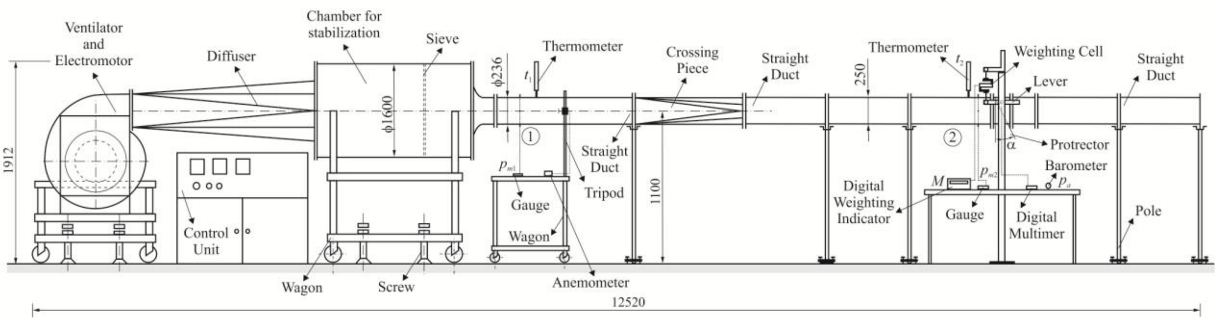

Figure 2. Schematic diagram of the laboratory facility for testing ATP dampers

A centrifugal fan driven by a DC motor supplies the airflow through the laboratory facility. The control unit regulates the airflow rates by adjusting the rotational speed of the fan blade. The accelerated air from the fan enters the diffuser, which converts the kinetic energy of the airstream into the pressure energy and partially breaks down the eddies occurring in the lee of the fan. The air from the diffuser flows into the laminarization chamber fitted with a sieve. The chamber and the sieve additionally subdue the eddies and supply the uniform airstream into the straight duct section for the air velocity measurements (1). The accurate measurement of the air velocity directly in front of the ATP damper blade (2) is not possible because of the presence of the blade in the airstream. The air velocity, v_1 [ms^{-1}], was measured in the straight duct section with a hot-wire anemometer, on the basis of the one-point method in accordance with the standard recommendations [8]. It was used a hot wire 1D anemometer manufactured by "Testo", model 425 (accuracy +/- [0.03% + 5% of measured velocity], frequency 2 Hz and sampling 1 s). A trolley with an adjustable stand was utilized for the positioning of the hot-wire anemometer. In addition to the air velocity in the straight duct section, the airstream temperature, t_1 [^oC], was measured with a mercury thermometer, as well as the airstream gauge pressure, p_{m1} [Pa], with a manometer. The airstream temperature, t_2 [^oC], and gauge pressure, p_{m2} [Pa], directly in front of the ATP damper blade were also measured. Air temperature was measured on the basis of the one-point method in accordance with the recommendations [9]. The atmospheric pressure, p_a [Pa], was measured with a digital barometer. From the mass flow rate equation in the sections (1) and (2), the average air velocity, v_2 [ms^{-1}], directly in front of the ATP damper blade was calculated.

The proper sealing of flanges was a key prerequisite of the presented indirect air velocity measurement in front of the ATP damper blade. The flanges were sealed with rubber seals. The straight duct sections preceding and following the damper shown in fig. 2 were constructed by flanging one-meter sections, which facilitated their assembling and dismantling for the purpose of installing the ATP dampers at three possible locations in HVAC systems. The mounting flanges were fitted with incrementally height-adjustable grooves, whereas the fan and the laminarization chamber were placed on the screw height-adjustable trolley. Consequently, the leveling of the fan, the laminarization chamber, and the groove section of the facility was established.

A laboratory 0.25 m x 0.25m ATP damper with replaceable blades was constructed for the experimental testing. Figure 3 displays a schematic diagram of the moment meter and the protractor for measuring the blade angle of attack of the laboratory ATP damper. The moment of airstream force exerted on the damper blade M was measured with the moment meter. The moment meter was constructed with a lever arm of length l, an airflow mass m sensor, and an electronic weighing scale for displaying the measured moment M. The blade was rigidly attached to the shaft, the shaft was rigidly bolted to the lever, and the lever was rigidly connected to the weighing cell by means of a spherical joint. Therefore, the moment of the airstream force exerted on the blade was transferred to the moment meter. The blade angle of attack was measured with a rotary potentiometer, which was calibrated in accordance with the protractor for monitoring the position of the blade (with the blade rotation axis displaced from the blade axis). The calibration procedures of the moment meter and the rotary potentiometer, their features, as well as the features of all the measuring equipment used were illustrated in great detail in the paper [4].

The air velocity measurement was performed within the range of 0-10 m/s, whereas the measurement of the blade angle of attack was within 0-90°. Two independent series of measurements were performed for each experiment. One set of measurements was used for the calibration of the ATP damper mathematical model (1), determination of a correlation function G (2), while another was utilized for the model verification. For all experiments the cross-sectional area upstream of the damper A_u and the hydraulic diameter D_h in eq. (1) are constant and known values.

The correlation function *G* is determined according to following procedure. Air density ρ in front of the damper is calculated from the ideal gas equation of state for measured values of air pressure *p* and temperature *t*. Correlation function *G* is determined from the eq. (1) by using of measured values of air velocity *v*, blade angle of attack α, moment of airstream force exerted on the blade *M* and air density ρ. ATP damper mathematical model (1) is calibrated when correlation function G is entered into model.

Verification of calibrated ATP damper mathematical model is carried out according to following procedure. Air density ρ in front of the damper is calculated from the ideal gas equation of state for measured values of air pressure *p* and temperature *t*. Empirically predicted velocity is determined from the calibrated mathematical model of ATP damper by using of measured values of blade angle of attack α, moment of airstream force exerted on the blade *M* and air density ρ. Verification of calibrated ATP damper mathematical model is done by comparing empirically predicted and measured velocity.

Four different blade profiles shown in fig. 4 were taken into account: A – a flat blade, B – a V-groove blade, C – a symmetrical airfoil blade, and D – a non-symmetrical airfoil blade. A non-symmetrical airfoil blade of the NACA 2412 type was used [10]. The geometry of the blade examined (fig. 5) indicated the uniformity of blade shaft diameters and mounting flange lengths. Minute differences were recorded in the blade tip clearances, which were adjusted to provide functionality to a given blade geometry, i.e. to meet the requirements of various blade positions.

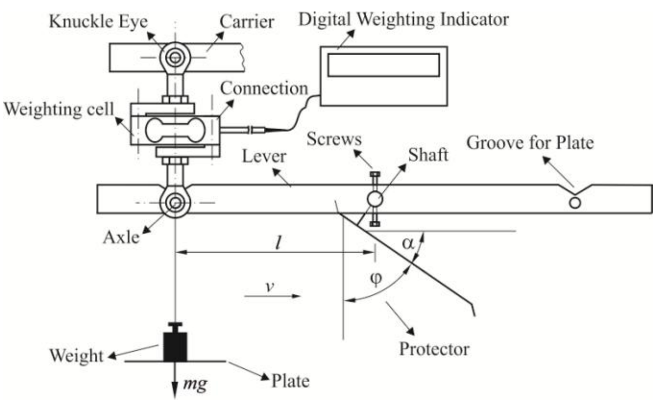

Figure 3. Schematic diagram of the ATP damper moment meter

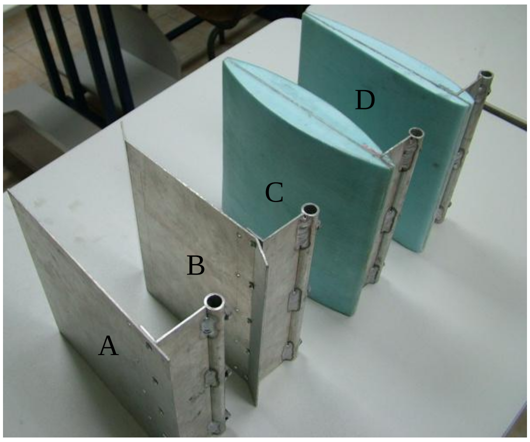

Figure 4. Appearance of the four blade profiles examined

The blades were fabricated from 2 mm aluminum sheets. The aluminum was selected as it is approximately three times lighter than steel, which significantly reduces the blade parasite moment (the moment being spent on the deflection of the blade, the moment of friction in bearings, the resistance moment of the transfer mechanism) [4]. The flat blade (A) and the V-groove blade (B) were constructed solely of aluminum, whereas the symmetrical airfoil blade (C) and the non-symmetrical airfoil blade (D) were reinforced with extruded polystyrene foam (XPS) additions, fig. 4. The mass of extruded polystyrene foam additions is minute in comparison with the mass of the blade and the XPS additions were coated with a thin layer of polyurethane resin, which contributed to the firmness and smoothness of the blade surface. During the fabrication of the airfoil blades, the XPS additions were glued to the both sides of the pivotal aluminum blade, fig. 4.

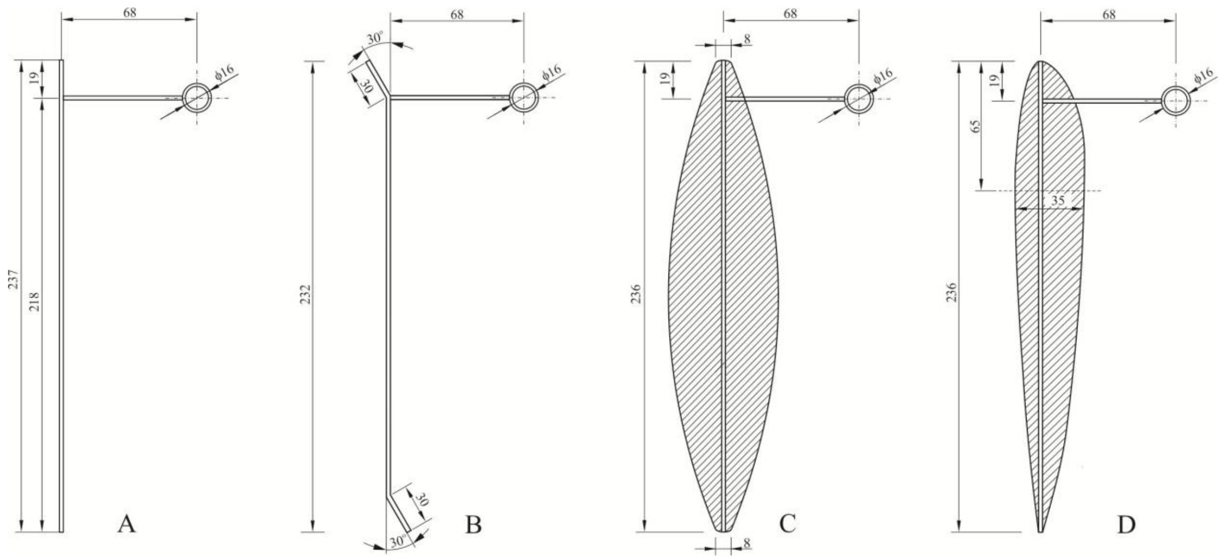

Figure 5. Geometry of the blade profiles examined

All three locations of ATP dampers in HVAC systems were examined: at the duct entrance, within the duct, and at the duct exit. Two blade orientations at the duct entrance were examined relative to the direction of airflow, which in total amounts to four separate sets of measurements: I – a damper at the duct entrance with a straight duct section following the damper (with a front mounting flange), II–a damper at the duct entrance with a straight duct section following the damper (with a rear mounting flange), III– a damper in the duct with straight duct sections both preceding and following the damper, and IV– a damper at the duct exit with a straight duct section preceding the damper. The straight duct sections, preceding and/or following the damper, were 3 m in all four measurement sets.

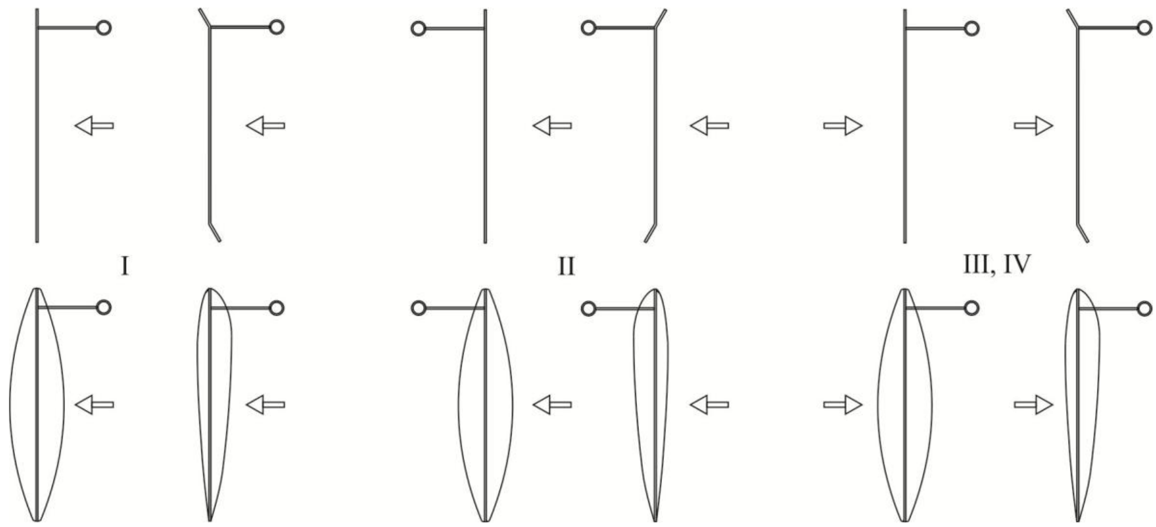

Figure 6. Blade orientations at different ATP damper locations in the system

3. Results and Discussion

According to previously described procedure correlation function *G* was determined by using of the first set of measurements. Figures 7-10 illustrate the experimentally obtained dependence of the correlation functions on the blade angle of attack in the instances of the four blade profiles examined and the four ATP damper locations in the system. The difference in correlation function values is caused by different blade profiles and different damper locations in the system.

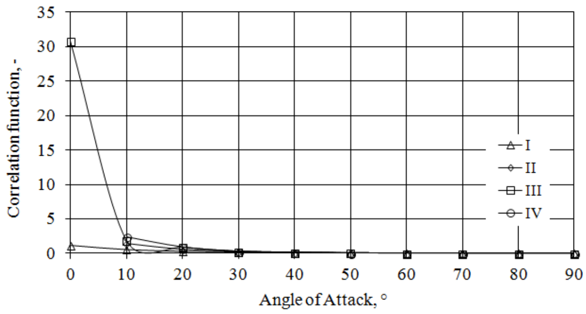

Figure 7. Correlation functions of the ATP dampers (A)

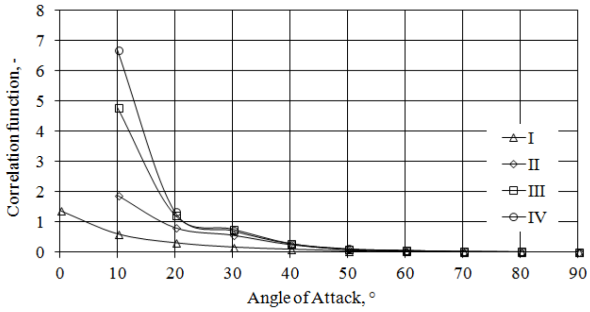

Figure 8. Correlation functions of the ATP dampers (B)

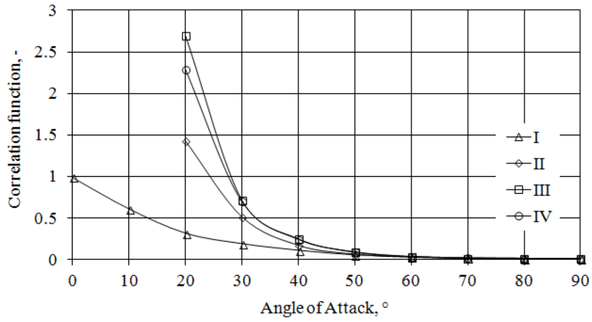

Figure 9. Correlation functions of the ATP dampers (C)

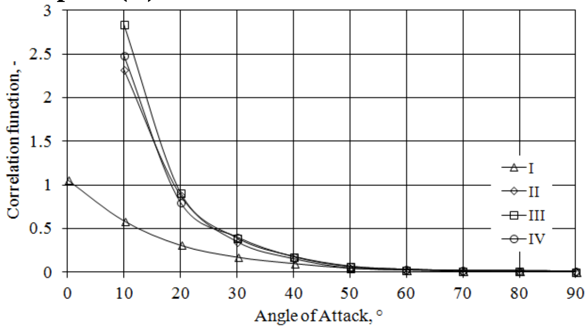

Figure 10. Correlation functions of the ATP dampers (D)

The difference in correlation functions is evident and markedly prominent when the ATP damper is more open, i.e. with lower blade angles of attack (the blade angle of attack is less than or equal to 30^{o}). Within the specified range of the blade angle of attack (characterized by the significant difference in correlation function values), the effects of blade profiles and damper locations in the duct system could be exerted on the accuracy of the air velocity measurements and the adequacy of the ATP damper model.

According to previously described procedure calibrated ATP damper mathematical model was verified by using of the second set of measurements. Figures 11-14 illustrate the empirically predicted velocity vs. the measured velocity for different blade profiles and different ATP damper locations in the system. It can be observed that the relative difference between the empirically predicted velocity vs. the measured velocity for the entire velocity range is mostly within the expected bounds of +/- 10%. The data obtained for certain blade profiles are outside the bounds of the performance target when the dampers are found at the following locations in the duct system: A-III, B-III and IV, C-III, and D-II, III and IV. A striking deviation from the expected results (outside the bounds of the performance target) was recorded in the instance of the non-symmetrical airfoil blade (D) when the damper was at the duct entrance with a rear mounting flange (II).

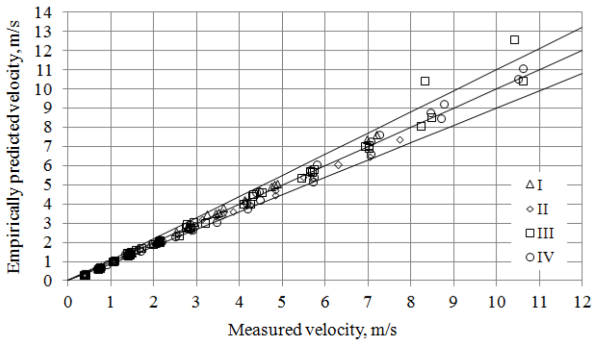

Figure 11. Empirically predicted velocity vs. the measured velocity (A)

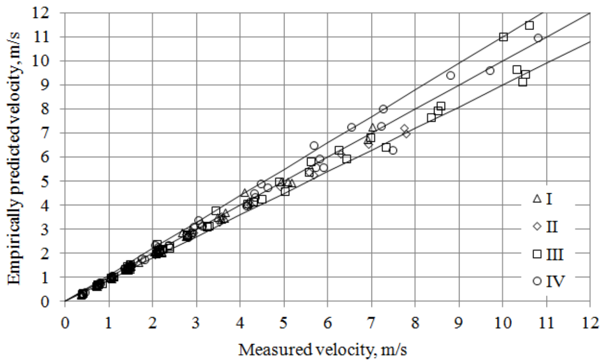

Figure 12. Empirically predicted velocity vs. the measured velocity (B)

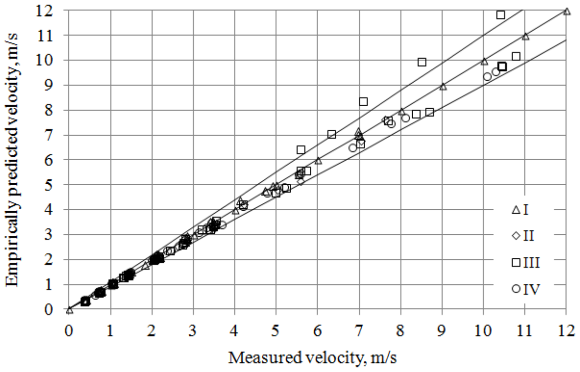

Figure 13. Empirically predicted velocity vs. the measured velocity (C)

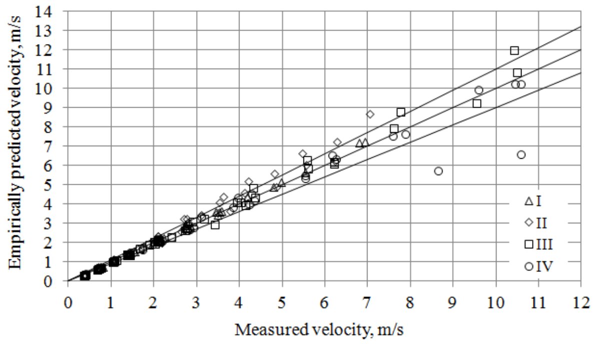

Figure 14. Empirically predicted velocity vs. the measured velocity (D)

The measurement set I, when the damper was installed at the duct entrance with a front mounting flange, is particularly noteworthy as the results obtained for all the examined blade profiles are within the bounds of the performance target. Therefore, it was indubitably confirmed that the damper location in the duct system exerts significant impacts on the measurement accuracy and the adequacy of the ATP damper mathematical model. Moreover, it was also observed that the blade orientation relative to the direction of airflow could affect the measurement accuracy and the adequacy of the ATP damper mathematical model.

The difference between the empirically predicted velocity and the measured velocity with regard to the angle of attack of different blade profiles was analyzed (fig. 15-18), at different damper locations in the system, in order to determine the angles of attack inducing significant deviations between the empirically predicted velocity and the measured velocity.

Provided the measurement set I is excluded from the analysis (because all the results obtained for this damper location are within the bounds of the performance target), the greatest difference between the empirically predicted velocity and the measured velocity is recorded in the instances of more open ATP dampers: B-III and IV (0-30^o), C-III (0-10^o), and D-II, III, and IV (0-20^o). The specified blade angles of attack are within the range of the lowest ATP damper sensitivity owing to the low moment of airstream force exerted on the blade.

The previously discussed analysis clearly indicates that there is no the best blade profile with regard to the accuracy of the air velocity measurements and the adequacy of the mathematical model because the measurement accuracy and the model adequacy are dependent on the damper location. The blade profile and particularly the damper location in the duct system greatly affect the measurement accuracy and the model adequacy provided the ATP damper is more open, i.e. the blade angle of attack is less than or equal to 30^o. The effects of the damper location on the accuracy of the air velocity measurements and the adequacy of the mathematical model are best illustrated by the damper location I, when all the results (even the ones obtained for more open ATP dampers) are within the expected bounds of +/- 10 %.

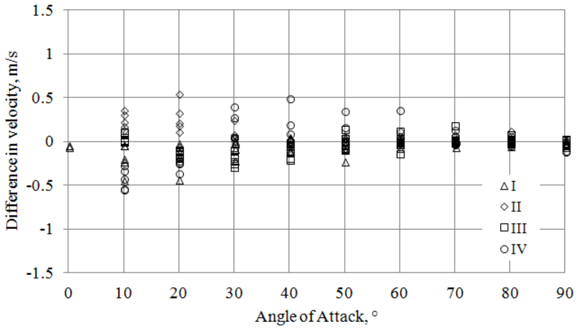

Figure 15. Difference between the empirically predicted velocity and the measured velocity (A)

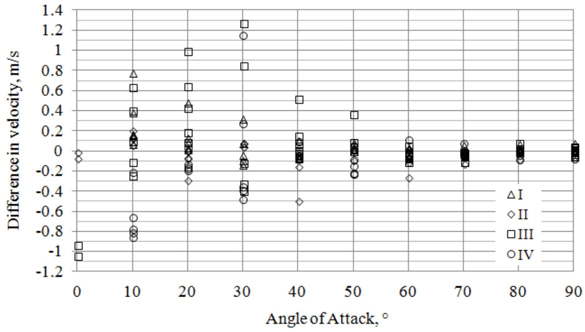

Figure 16. Difference between the empirically predicted velocity and the measured velocity (B)

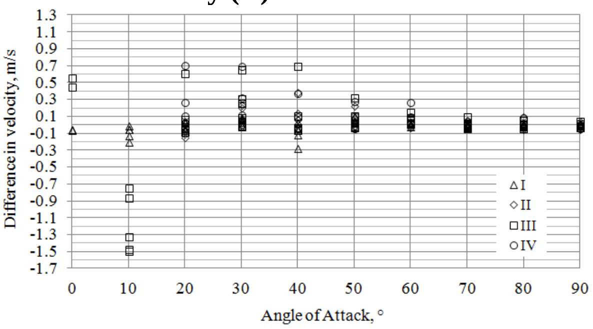

Figure 17. Difference between the empirically predicted velocity and the measured velocity (C)

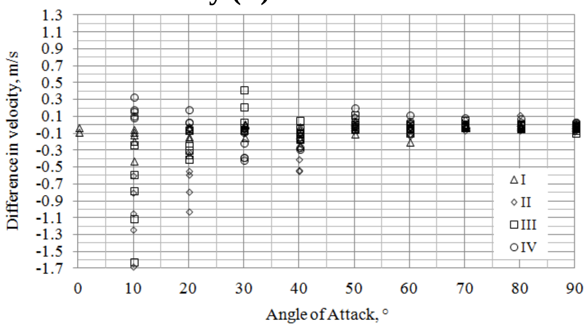

Figure 18. Difference between the empirically predicted velocity and the measured velocity (D)

Finally, it should be stated that Federspiel [2], by inducing the local resistance in front of the damper, argued that the difference between the empirically predicted velocity and the measured velocity will be outside the expected bounds of +/- 10% or 5% of the full-scale velocity in the instance of a more open damper (when the damper is more than 70% open). The effects of blade profiles and damper locations in the duct system (on the measurement accuracy and the model adequacy) argued in this paper are consistent with the findings that ATP dampers are highly prone to impacts when they are more open, i.e. with the low moment of airstream force exerted on the damper. The specified impacts can be neutralized for the purpose of air velocity measurements provided the blade angle of attack is set to render the damper more closed, which will undoubtedly increase the damper sensitivity and the accuracy of air velocity measurements [11] with a simultaneous increase in the damper pressure drop and energy dissipation [12].

4. Conclusion

The primary concern of this paper is a single-blade air torque position damper used for the indirect measurement of volumetric airflow rates by measuring the moment of airstream force exerted on the blade and the blade angle of attack. The purpose of the paper is to analyze the accuracy of the air velocity measurements and the adequacy of the damper mathematical model on the basis of the blade profile and the damper location in a duct system. Four different blade profiles (flat, V-groove, symmetrical airfoil and non-symmetrical airfoil blades) were taken into account, as well as four different damper locations in the duct system: at the duct entrance (with a front mounting flange), at the duct entrance (with a rear mounting flange), within the duct, and at the duct exit.

In the paper was experimentally proven that blade profiles exerted certain and damper locations significant effects on the measurement accuracy and the ATP damper model adequacy. The effects of blade profiles and particularly damper locations in the duct system occur at lower blade angles of attack (the blade angle of attack is less than or equal to 30^{o}), when the ATP damper is less sensitive owing to the low moment of airstream force. Within the specified range of the blade angle of attack, there is no the best blade profile because each blade profile depends on the damper location in the duct system with regard to the measurement accuracy and the ATP damper model adequacy. The impacts of the damper location in the duct system on the measurement accuracy and the ATP damper model adequacy are best illustrated when the damper is located at the duct entrance with a front mounting flange because the relative difference between the empirically predicted velocity vs. the measured velocity for all the blade profiles examined and the entire range of the blade angle of attack is within the expected bounds of +/- 10%. It can be concluded that the damper location at the duct entrance (with a front mounting flange) is the best regarding the accuracy of the air velocity measurements.

The results obtained indubitably necessitate a further confirmation of the universal features of the ATP damper, which could prove to be adequate for dampers with different cross sections, designs, blade numbers and operations (actions), locations in HVAC systems, etc. It was determined that the blade orientation relative to the airflow could affect the measurement accuracy and the ATP damper model adequacy, thus the effects of blade orientation ought to be analyzed in greater detail in prospective research. Moreover, the impacts of blade profiles and damper locations in the duct system on the ATP damper pressure drop and energy dissipation should also be examined in the future.

Acknowledgments

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Nomenclature

A - cross-sectional area, [m^2]
C_Q - flow coefficient, [-]
d - distance from the midpoint of the chord to the center of pressure, [m]
D -diameter, [m]
F - force, [m]
g - gravitational constant, [ms^{-2}]
G - correlation function, [-]
H - duct height, [m]
l - lever arm length, [m]
L - blade length, [m]
m - mass, [kg]
M - torque, [Nm]

p - pressure, [Pa]
t - temperature, [^{o}C]
v - velocity [ms^{-1}]
x - axial distance from the axle to the center of pressure, [m]
y - lateral distance from the axle to the center of pressure, [m]

Greek symbols

α - angle of attack, [^{o}]

φ - blade position normal to the vertical, [^{o}]

δ - distance between the center of axle and the damper blade, normal to the damper blade, [m]

Δ - distance between the center of axle and the damper blade, parallel to the damper blade, [m]

ρ - air density, [kgm^{-3}]

Abbreviations

ATP -Air Torque Position

HVAC - Heating Ventilation Air Conditioning

NACA- National Advisory Committee for Aeronautics

Indexes

1 - location of air velocity measurements, blade

2 - location directly in front of the blade, blade mounting flange

a - longitudinal, atmospheric

C - center of bladeaxle

c - contraction

d - downstream

h - hydraulic

l - lateral

m - manometer

n - normal

u - upstream

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