Teknillinen korkeakoulu. Konetekniikan osasto. LVI-tekniikan laboratorio. A

Helsinki University of Technology. Department of Mechanical Engineering.

Laboratory of Heating, Ventilating and Air Conditioning. A

Espoo 2004

DUST IN VENTILATION DUCTS: ACCUMULATION, MEASUREMENT AND REMOVAL

REPORT A9

Rauno Holopainen

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Mechanical Engineering, Helsinki University of Technology for public examination and debate in Auditorium K216 at Helsinki University of Technology (Espoo, Finland) on the 26th of March, 2004, at 12 noon.

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ISBN 951-22-6976-7 (PDF format)
ISBN 951-22-6975-9 (printed format)
ISSN 1238-8971

Otamedia Oy
2004

ABSTRACT

This thesis focuses on dust accumulation in, and removal from, recently installed supply air ducts and on the bristle behaviour of rotating duct cleaning brushes. The results of dust accumulation, measured using three different methods, were compared and the amount of dust in newly installed air ducts was evaluated. The vacuum test was found to be an efficient method of collecting dust samples on the duct surface. The vacuum test and the gravimetric tape method gave approximately the same results when the measured dust accumulation on the duct surfaces was 0.1–1.0 g/m^2. The gravimetric and optical tape methods can be used to evaluate cleanliness of new ducts when the amount of dust accumulation is 0.1–1.0 g/m^2.

The effect of protection measures on dust accumulation was studied. The mean amount of accumulated dust after construction was 0.9 g/m^2 in cleanliness category P1 ducts, which have special requirements for oil residues and protection measures against contamination during construction, and 2.3 g/m^2 in cleanliness category P2 ducts, which have only minor protection requirements and are for normal use. The results show that dust accumulation in category P1 ducts was significantly lower ($P < 0.008$) than in category P2 ducts. The highest mean amount of dust accumulation was found in the middle of the ducts and the lowest amount near the air handling units.

The efficiency of two dry air duct cleaning methods applied to new air ducts was compared. Mechanical brushing and compressed air cleaning methods were found to be efficient in removing dust from the newly installed air duct surfaces. Mechanical brushing was more efficient in metal ducts, while the compressed air cleaning method was more efficient in plastic ducts. The mean amount of residual dust on the duct surfaces was below 0.4 g/m^2 after duct cleaning. However, neither of the cleaning methods studied was efficient enough to clean ducts that had a high level of residual oil (216–338 mg/m^2) on the duct surfaces.

A mathematical model to simulate the behaviour of a single bristle of a rotating duct cleaning brush was developed. The results of the simulation were compared with those obtained from a laboratory test. The simulated and experimental results were found to be in reasonable agreement. The dependence of the normal force and the contact angle as a function of various parameters was studied. The simulation and experimental results showed that the normal force and contact angle increase as a function of the rotation speed. Further, the thickness of the bristle was found to have a strong effect on the normal force. Air drag has only a slight effect on the deflection of the bristle. The model can be used as a first step in the systematic design of brushes. However, further theoretical and experimental research is needed to determine the dependency, for instance, between the brush tip normal force and its cleaning efficiency.

PREFACE

This thesis is based on studies undertaken during the period 1998−2003 at the Laboratory of Heating, Ventilating and Air Conditioning (HVAC), Helsinki University of Technology. The work was part of the Clean Ventilation Systems and the Duct Cleaning Concept projects funded by the National Technology Agency of Finland (Tekes). Additionally, I was granted scholarships from the Department of Mechanical Engineering at Helsinki University of Technology, the Research Foundation of Helsinki University of Technology, as well as the K.V. Lindholm Foundation and the L.V.Y. Foundation, all of whom I would like to thank for their support.

I wish to express my deepest gratitude to my supervisors Professor Olli Seppänen and acting Professor Pertti Pasanen for their guidance, encouragement and invaluable support during my study. Additionally, I sincerely thank Professor Olli Seppänen for providing me the opportunity to work in an independent university environment.

I am very grateful to Emeritus Professor Eero-Matti Salonen for his invaluable advice and dedicated guidance in mechanics during the preparation of my thesis. I would like to thank him very much for this and the other help and support he gave me.

I would like to express my sincere thanks to Emeritus Professor Matti A Ranta and Dr. Thomas Schneider for their constructive criticism and comments on my dissertation manuscript.

I would like to thank to Professor Pertti Laininen for his advice during the statistical analysis of field results and laboratory tests, and to the manager of the HVAC-laboratory, Markku Sivukari, and Petteri Kivivuori, laboratory technician, for arranging these tests. My thanks go to Marko Björkroth and Vesa Asikainen for their help with the laboratory tests of the duct cleaning methods, to Marianna Tuomainen and Jarkko Narvanne for their help with the field measurements, Iikka Järvenpää, the manager of the Mechanics and Materials laboratory, for his valuable comments on the rotating-brush test, and Petteri Martonen for his preliminary rotating-brush test. Additionally, I would also like to thank all my colleagues, especially Ala Hasan, Antti Majanen, Ari Seppälä, Jari Palonen, Jarkko Heinonen, Walter Kotiaho, Dr. Birgit Müller, Dr. Jarek Kurnitski and Dr. Miimu Airaksinen, for many fruitful discussions during my study.

Further, my thanks go to Ruth Vilmi in the English Department, Leila Sarajärvi in the Finnish Society of Indoor Air Quality and Climate (FiSIAQ) and Marianna Tuomainen in the HVAC-laboratory for their valuable advice in the field of English language and the secretary of the HVAC-laboratory, Pirkko Salo, for her help in practical office arrangements.

Finally, I wish to give warm thanks to my wife Anne and our children Jukka and Niina for their flexibility and love.

Espoo, February 2004

Rauno Holopainen

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the results presented in the following publications, which are referred to in the text by the following Roman numerals:

I Holopainen R, Asikainen V, Pasanen P, Seppänen O (2002). The field comparison of three measuring techniques for evaluation of the surface dust level in ventilation ducts, *Indoor Air*, **12**, 47–54.

II Holopainen R, Tuomainen M, Asikainen V, Pasanen P, Säteri J, Seppänen O (2002). The effect of cleanliness control during installation work on the amount of accumulated dust in ducts of new HVAC installations, *Indoor Air*, **12**, 191–197.

III Holopainen R, Asikainen V, Tuomainen M, Björkroth M, Pasanen P, Seppänen O (2003). Effectiveness of duct cleaning methods on newly installed duct surfaces, *Indoor Air*, **13**, 212–222.

IV Holopainen R, Salonen E-M (2003). Modelling bristle behaviour in rotating brush duct cleaning, *Helsinki University of Technology*, *Department of Mechanical Engineering*, *Laboratory of Heating*, *Ventilating and Air Conditioning*, *Report B75*, Espoo, Finland.

V Holopainen R, Salonen E-M (2003). Large deformation analysis of a rotating bristle in brush duct cleaning. In: *1st CEACM Conference on computational mechanics (CMM-2003)*, *Paper 060P published on CD-ROM*.

VI Holopainen R, Salonen E-M (2004). Rotating brush behaviour in duct cleaning. Accepted for publication, in a shortened form, in the *Energy and Buildings - REHVA Scientific* on 25th February 2004.

The disputant served as the main author of all the publications. In I, preliminary laboratory tests on dust collection efficiency and hygroscopic properties of the measuring methods for dust were carried out by Vesa Asikainen and Dr. Pertti Pasanen, who also carried out the laboratory analysis of oil residual in III. In II–III, the disputant carried out the field measurements with Marianna Tuomainen. In III, Vesa Asikainen, Marianna Tuomainen and Marko Björkroth assisted the disputant in the laboratory tests. Professor Eero-Matti Salonen gave support for formulating the rotating cleaning brush problem in IV–VI.

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NOMENCLATURE

A	cross-sectional area of bristle, measured value of optical method
c	dimensionless multiplier
$c_0, c_1, ..., c_n$	undetermined parameters
CAC1,...,CAC3	compressed air cleaning method types
C_D	air drag coefficient
CI	confidence interval
$CTOL$	constraint tolerance
d	thickness of bristle
$\mathrm{d}m$	differential mass element of bristle
$\mathrm{d}s$	differential bristle length element
E	Young's modulus of bristle material
EI	flexural rigidity of bristle
F-test	significance tests on two population variances
L	length of bristle
$L_1, L_2, ..., L_m$	Lagrangian interpolation functions
M	bending moment
MB1,..., MB10	mechanical brushing method types
$M_1, M_2, ..., M_j$	first integrals of Lagrangian interpolation functions
n	rotation speed of bristle, degree of approximation, number of bristles
N	magnitude of normal force
$N_1, N_2, ..., N_j$	second integrals of Lagrangian interpolation functions
P	probability, cross-sectional normal force
P1, P2	cleanliness categories of air ducts
q	air drag force per unit bristle length acting normal to bristle
Q	shearing force
r	radial distance from origin to s
R	radius of duct
R^2	multiple correlation coefficient
RCE	relative collection efficiency
Re	Reynolds number $= vd/\nu_\mathrm{a}$
RSD	relative standard deviation
s	arc length coordinate of a generic point of bristle
$s_1, s_2, ..., s_m$	interpolation points in interval $0 \le s \le L$
T	torque
T-test	significance tests on two population means
TOL	convergence tolerance
v	speed of cylinder with respect to air, speed of airflow into duct
W_t	amount of dust accumulation gram per square meter measured with gravimetric tape method
x, y	coordinates of a generic point of bristle

Greek symbols	
α	polar angle
β	bristle tip contact angle
γ	angle between rod normal and rod velocity vector
ζ	bristle length radius ratio L/R
θ	inclination angle of bristle axis with x-axis
μ	kinetic coefficient of friction
ν_a	kinematic viscosity of air
ξ	ratio s/L
π_1	dimensionless number $= \rho_b A\omega^2 L^4 / EI$
π_2	dimensionless number $= L/R$
π_3	dimensionless number $= \mu$
π_4	dimensionless number $= c^2 \rho_a \omega^2 L^5 d / EI$
π_5	dimensionless number $= c\omega Ld/\nu_a$
ρ	density
ϕ	inclination angle of a ray to s with respect to x-axis
ω	angular speed of brush
Subscript	
a	air
ad	air drag
b	bristle
c	dimensionless multiplier
bf	bearing friction
fit, fitF	fitting functions
lo	lower limit
N	air drag intensity normal to axis
r	polar coordinates of duct
s	simulated value
t	corrected value of optical method
up	upper limit
μ	contact friction
Superscript	
*	first level integration points, torque from one bristle
'	second level integration points, point inside of end part of bristle
–	dimensionless quantity
~	approximation of a quantity

1 INTRODUCTION

Air ducts and air handling systems may be potential sources of pollutants in buildings. Dusty surfaces cause hygiene risks (Pasanen, 1998), decrease airflow rate (Wallin, 1994), may increase energy consumption and may cause malfunctions in air handling systems. Recent laboratory measurements have shown that both new and old supply ducts may be sources of sensory pollution (Björkroth et al., 1997a; Björkroth et al., 1997b; Björkroth and Asikainen, 2000). Although the cleaning of air handling systems has been found to improve the perception of working environments and has reduced the prevalence of sick-building symptoms in office buildings (Kolari, 2003), agreement on the required cleanliness levels has not yet been achieved. Clean air ducts are an essential part of achieving good indoor air quality, even though the lack of scientific knowledge in this field is reflected in international discussions and no consensus as to cleanliness criteria has been found (Pasanen et al., 2000).

The cleanliness of air ducts has been taken into consideration during the last few years particularly. Dust accumulation in newly installed air ducts was found to be high when attention had not been paid to the cleanliness of the ducts during construction (Pasanen, 1998; Luoma, 2000). Dust and other impurities in new ducts originate particularly from installation work and when the particle concentration is high at the building site (Luoma, 2000). After the construction process, pollutants accumulate on duct surfaces during the operation of the air handling system. During the operation, the main causes of dust accumulation in the supply air duct are polluted outdoor air and the inadequate maintenance of the filters (SNBH, 1994). Highly efficient filtration protects supply air ducts during the operation of the system and thus can increase the length of cleaning intervals (SNBH, 1994; Wallin, 1994; Fransson et al., 1995; Pasanen, 1998).

Dust accumulation on the duct surface may be evaluated using a number of different measuring methods developed for various purposes (NADCA, 1992; Juell et al., 1994; JADCA-01, 1997; JADCA-02, 1997; WintTest, 1997; HVCA, 1998; Pasanen, 1999; VDI, 2001). The simplest and most commonly used evaluation method is visual inspection, which is considered a primary method of evaluating the need for cleaning during the commissioning process (Holopainen et al., 2002) and the periodic inspection (NADCA, 2003) as well as of verifying the cleanliness of the ductwork after duct cleaning (HVCA, 1998; NADCA, 2001; NADCA, 2003). However, further objective measurements are needed if the inspector cannot make a clear decision as to whether the ducts should be re-cleaned or certified as having been cleaned adequately. The results of the evaluation should be reported (HVCA, 1998; NADCA, 2003) and documented (Holopainen et al., 2003) for the next periodic inspection. Figure 1.1 presents a simplified procedure for the inspection and cleaning of air ducts and air handling systems.

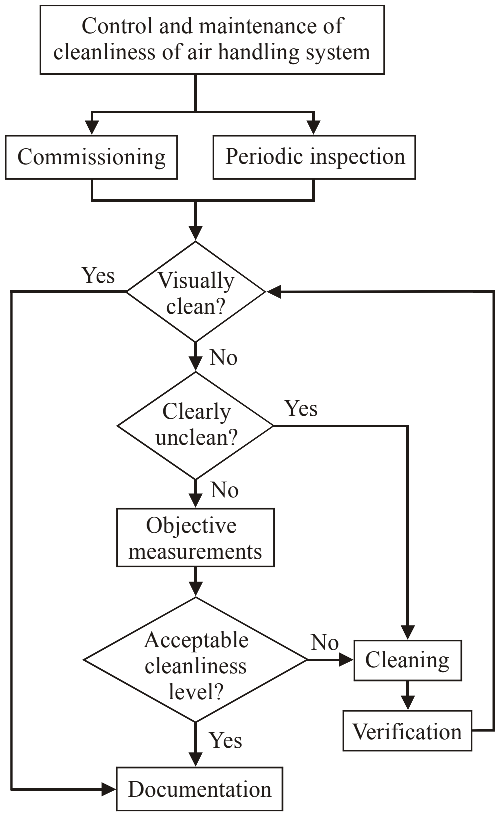


Figure 1.1. Schematic flow chart for procedures to maintain cleanliness of an air handling system.

In some countries, the cleanliness of air ducts is inspected at regular intervals (SNBH, 1994; VDI, 1998; NADCA, 2001; FiSIAQ, 2001). In other countries, air ducts are either cleaned regularly according to a schedule (HVCA, 1998; MI, 2001) or when dust accumulation on the duct surface exceeds the given limit value (SNBH, 1994; HVCA, 1998; FiSIAQ, 2001; VDI, 2001). Some organizations have also presented the limit values for acceptable dust accumulation in order to verify the cleaning results after duct cleaning (NADCA, 1992; Juell et al., 1994; JADCA-01, 1997; HVCA, 1998).

In this study, three objective measuring techniques for evaluating dust accumulation in newly installed air ducts and the results of the effect of cleanliness control defined in (FiSIAQ, 2001) during installation work on the dust accumulation in ducts are compared. The results of the efficiency of two dry duct cleaning methods, the simulation results of the developed model for rotating brushes, and a comparison of the results obtained in laboratory tests are presented.

2 REVIEW OF THE LITERATURE

2.1 Measuring dust accumulation

Dust accumulation in air ducts is normally evaluated using gravimetric methods, the optical method, or by measuring the thickness of the dust layer or visually. The principles and purposes of the methods vary and they may each give different results (Fransson et al., 1995; JADCA-01, 1997; Fitzner et al., 2000). The dust measuring methods have been developed to evaluate the need for cleaning (Valbjørn et al., 1990; Ito et al., 1996; WintTest, 1997; HVCA, 1998; Pasanen, 1999; VDI, 2001; Asikainen et al., 2003a) or to verify of the quality of duct cleaning work (NADCA, 1992; Juell at al., 1994; JADCA-02, 1997). Some of the methods are used to obtain quantitative data for research purposes (Pasanen, 1998; VDI, 2001). The visual inspection method is commonly used for evaluating both the need for cleaning (Holopainen, et al., 2003; NADCA, 2003) and verifying the quality of duct cleaning work (Juell at al., 1994; HVCA, 1998; NADCA, 2001; Holopainen, et al., 2003; NADCA, 2003).

The gravimetric vacuum test method is especially used as a reference method for evaluating the dust accumulation on the duct surface (NADCA, 1992; FiSIAQ, 2001). The dust sampling technique of the vacuum test method affects dust sampling efficiency (Fransson et al., 1995; Fitzner et al., 2000). The gravimetric wiping method that uses non-woven cloth (Ito et al., 1996), or cloth applied with solvent (Fitzner et al., 2000), is an efficient method of collecting dust on the duct surface. The gravimetric tape method is fast and applicable to relatively low dust accumulation in the field (Fransson et al., 1995; Pasanen, 1999).

The optical method with gelatine tapes (Schneider et al., 1996) or with semi-transparent engineering adhesive tapes (JADCA-02, 1997) is used to evaluate the cleanliness of air ducts, especially after duct cleaning (Juell at al., 1994; JADCA-02, 1997). The operating principle of the method is based on the change in the light extinction through a transparent sampling tape. The amount of dust on the surface is expressed as a percentage of reduction of the light extinction through the contaminated tape compared to that of a clean tape (Schneider et al., 1996).

The deposit thickness test (D.T.T.) method with an instrument (HVCA, 1998) or with a comb (Asikainen et al., 2003a) is used to evaluate the cleanliness of a duct surface. The instrument of the thickness test method is based on electromagnetic measurements of the distance from the dust surface to the sheet metal surface. The method has been introduced as an alternative method to the vacuum test method in guidelines published in UK (HVCA, 1998). The comb method is based on a simple instrument equipped with a scale for measuring the thickness of the dust layer (Asikainen et al., 2003a).

The visual evaluation method is recognized as the primary method of evaluating the cleanliness of a duct (Holopainen et al., 2003; NADCA, 2003); apart from this, it may be applied together with other objective measuring methods upon completion of the duct cleaning work (NADCA, 1992; HVCA, 1998; NADCA, 2001). A visual inspection procedure was developed to help trained and experienced inspectors evaluate systematically the amount of dust on the duct surface (Holopainen et al., 2002). Special inspection tools such as borescopes, mirrors and remote-controlled video-camera robots with appropriate illumination capability may be used with the help of visual inspection (NADCA, 1992; NADCA, 1995; NADCA, 2003). The properties of the various evaluation methods are summarized in Table 2.1.

Table 2.1. Properties of dust sampling methods.

Evaluation method	Analysis of sample	Detection limit or accuracy	Most common application	Unit of quantity	Reference
Vacuum test (NADCA-test 3)	Laboratory	0.001 g/m^2 [a]	Evaluation of cleaning work	g/m^2	NADCA, 1992
Vacuum test (FiSIAQ-test 2)	Laboratory	0.001 g/m^2 [a]	Evaluation of need for cleaning	g/m^2	Pasanen, 1999
Vacuum test (WintTest)	Laboratory	0.001 g/m^2 [a]	Evaluation of need for cleaning	g/m^2	WintTest, 1997
Wiping (JADCA-01)	Laboratory	0.001 g/m^2 [a]	Evaluation of need for cleaning	g/m^2	Ito et al., 1996
Wiping with solvent (VDI)	Laboratory	0.001 g/m^2 [a]	Evaluation of need for cleaning	g/m^2	Fitzner et al., 2000
Gravimetric tape (Tape)	Field	0.1 g/m^2 [b]	Evaluation of need for cleaning	g/m^2	Fransson et al., 1995
Optical (BM-Dustdetector)	Field	0.1% [c]	Evaluation of cleaning work	%	Schneider et al., 1996
Optical (JADCA-02)	Field	– [d]	Evaluation of cleaning work	%	JADCA-02, 1997
Thickness test (D.T.T.)	Field	±3 µm [e]	Evaluation of need for cleaning	µm	HVCA, 1998
Thickness test (Comb)	Field	±25 µm [f]	Evaluation of need for cleaning	µm	Asikainen et al., 2003a
Visual (NADCA-test 1)	Field	– [g]	Evaluation of cleaning work	–	NADCA, 2001
Visual (NADCA-test 2)	Field	– [h]	Evaluation of cleaning work	–	NADCA, 2001
Visual (FiSIAQ-test 1)	Field	0.3 g/m^2 [i]	Commissioning for new air ducts	g/m^2	Narvanne et al., 2002

Detection limit:
[a] When the resolution of the laboratory balance is 0.01 mg and the sampling area 100 cm^2
[b] When the resolution of the field balance is 1.0 mg and the sampling area 100 cm^2
Accuracy:
[c] Accuracy of the equipment
[d] Not reported
[e] Requirement for accuracy of the equipment
[f] Based on the scale of the comb: 10 µm, 35 µm, 60 µm, 85 µm, 110 µm, 135 µm
Visual method:
[g] If a component is visually clean then no further cleanliness verification is required
[h] Surface comparison test with the contact vacuum equipment
[i] Accuracy is based on dust accumulation of the reference scale: clean, 0.2 g/m^2, 0.4 g/m^2, 0.7 g/m^2, 1.0 g/m^2, 1.3 g/m^2

2.2 Dust in newly installed air ducts

Dust accumulates in newly installed air ducts from the manufacturing process, transportation, storage and installation of air handling systems (Pasanen, 1998). Ducts should be protected against dust during the whole construction process, in which the aim is to achieve a clean installation (CEN, 1997; FiSIAQ, 2001). According to (Pasanen, 1998), dust accumulation in recently built supply air ducts was, on average, 5.1 g/m^2 (0.2–8.4 g/m^2). In a more recent study, average dust accumulation varied by 0.5–4.9 g/m^2, depending on the protection measures (Luoma, 2000).

Dust accumulation in air ducts may be high during installation work and when the particle concentration at the building site is high (Luoma, 2000). Non-abrasive cutting methods, such as those that use plate shears, are recommended for the installation work of air handling systems (Luoma and Kolari, 2002). Additionally, the surfaces of the spaces in the building should be cleaned sufficiently often after the dust-producing work to prevent the re-suspension of dust particles from deposits on the surfaces in the ambient air (FiSIAQ, 2001).

The guidelines (SNBH, 1992; Juell et al., 1994; FiSIAQ, 2001) give limit values for dust accumulation in newly installed air ducts, while the guidelines (CEN, 1997; VDI, 1998; FiSIAQ, 2001; VDI, 2001) give detailed instructions as to how to construct a clean ventilation system. Table 2.2 presents the requirements for dust accumulation of newly installed air ducts and air handling systems.

Table 2.2. Limit values for dust accumulation in newly installed air ducts and air handling systems.

Country	Application	Category	Prior to clean ducts	Evaluating method	Reference
Finland	Supply	P1 [a] P2 [a]	1 g/m^2 2.5 g/m^2	Visual [d] or Vacuum test [e]	FiSIAQ, 2001
Germany	General	High [b] Middle [b] Basic [b]	Visually unclean Visually unclean Heavy dirt	Visual [f] Visual [f] Visual [f]	VDI, 1998
Norway	Supply	Class A [c] Class B [c]	3% 5%	Optical [g] Optical [g]	Juell et al., 1994
Sweden	Supply	–	1 g/m²	Not mentioned [h]	SNBH, 1994
USA	General	–	Visually unclean	Visual [i]	NADCA, 2001

Categories:
[a] cleanliness categories
[b] cleanliness levels
[c] cleanliness class levels
Evaluating methods:
[d] Visual inspection with a reference scale as the primary method (Narvanne et al., 2002)
[e] Vacuum test (FiSIAQ-test 2) (Pasanen, 1999)
[f] Requirements for specific categories (A and B) and training to inspectors before they are authorised to inspection work (VDI, 1999)
[g] Optical method with gelatine tapes (Schneider et al., 1996)
[h] Requirements for specific qualification (classes K and N) and experience to inspectors before they are authorised to inspection work
[i] Requirements for qualification and experience to inspectors before they are authorised to inspection work

The Finnish guideline (2001) includes two cleanliness categories for air ducts. Cleanliness category P1 requires the protection of the open ends of the ducts during storage and transportation, as well as after they have been installed. The components used in category P1 should meet the oiliness and dustiness requirements. The limit value for oiliness is ≤50 mg/m^2 and for dustiness ≤0.5 g/m^2. In category P2, only minor requirements have been set for maintaining the cleanliness of the ducts and their components.

2.3 Air duct cleaning

Professional air duct cleaning contractors have used several cleaning methods to clean air ducts. The cleaning methods are chosen with the aim of achieving acceptable cleaning results without causing damage to the surface or to the components of ductwork (NADCA, 1995; HVCA, 1998). The European pre-standard (CEN, 1997) requires the specification of the cleaning methods to be used for periodical duct cleaning.

The duct cleaning methods can be considered to be dry or wet methods (CEN, 1997; HVCA, 1998). Commonly used dry cleaning methods include compressed air cleaning, hand vacuuming and mechanical brushing (Luoma et al., 1993; NADCA, 1995; CEN, 1997; HVCA, 1998; NADCA, 2001). The main principles of these methods are the same; dust is dislodged from the duct surfaces and conveyed from the duct using the movement of airflow by a vacuum collector to a filter unit where the particles are collected (Figure 2.1). The vacuum collection device might be a significant source of pollutants in the building (Puhakka et al., 1992; NADCA, 1995), particularly if the exhaust air is supplied back into occupied during duct cleaning work. The cleaning direction of the ducts is normally the same as the airflow in the ductwork during the operation of the air handling system (NAIMA, 2003). Wet cleaning methods are seldom used to clean air ducts because ductwork is not normally designed to be watertight. Table 2.3 presents three commonly used dry cleaning methods for air ducts.

Table 2.3. Dry cleaning methods and their properties (modified from HVCA, 1998).

Cleaning method	Method of removing deposit	Most common application
Compressed air [a]	Air washing the surface of the ductwork using air nozzle (a plastic or metal ball) placed on the end of a flexible cleaning hose	To clean surfaces of ductwork which can damage using mechanical contact
Hand vacuuming	Brushing and suction using a brush head appropriate for the purpose	To clean limited area of ductwork
Mechanical brushing [a]	Brushing the surface of the ductwork using a brush and mechanical action	To clean ductwork containing dry and loose atmospheric deposits

[a] Vacuum collection device with appropriate air filters shall be used to convey and capture dust dislodged during the cleaning process

The compressed air cleaning method is used to clean air duct surfaces such as concrete ducts, which can be damaged using other cleaning methods. The compressed air cleaning method consists of an air nozzle connected to a pneumatic cleaning hose, an air compressor, a vacuum collector with a vacuum hose and a filter unit (NAIMA, 2003). The compressed air is led into the duct from the compressor through the cleaning hose to the air nozzle, which is guided into the ducts with the hose. The airflow and pressure needed for the compressor depend on the type of the air nozzle.

Hand vacuuming is commonly used to clean a limited area of ductwork such as the area immediately surrounding access openings. Additionally, hand vacuuming is often needed to finish duct cleaning work. The hand vacuuming method consists of a vacuum nozzle equipped with a brush head, a vacuum source with a vacuum hose and a filter unit (NAIMA, 2003). The brush head is guided into ducts by hand and the dislodged dust is conveyed from the duct surface by the airflow along the vacuum hose to a filter unit.

Mechanical brushing is a commonly used cleaning method, particularly for cleaning round metal ducts. The brushing systems consist of a rotating brush, a power source with a flexible rotating shaft, a vacuum collector with a vacuum hose and a filter unit (NAIMA, 2003). The movement of the rotated brush is guided into the ducts with the shaft. Figure 2.1 presents the schematic diagram of a mechanical brushing system.

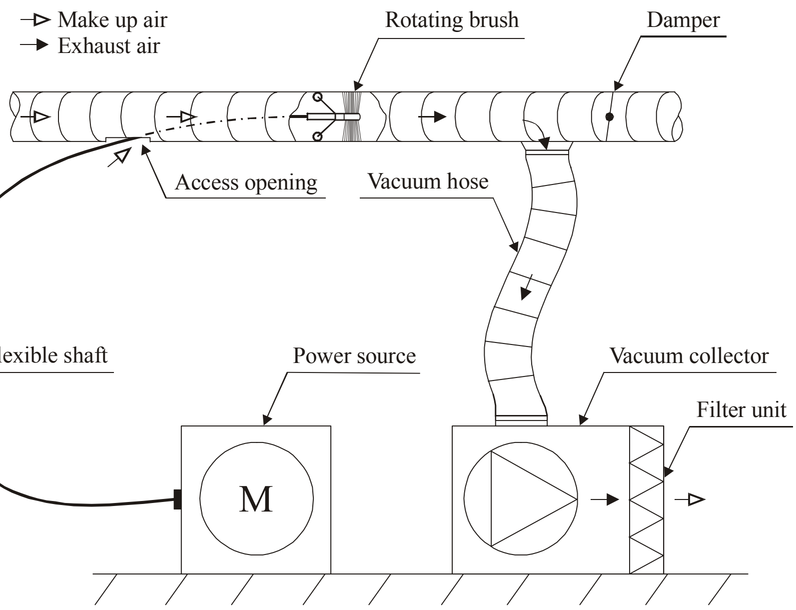


Figure 2.1. Schematic diagram of a dry air duct cleaning system using mechanical brushing.

To date, rotating duct cleaning brushes have been mostly designed using empirical methods and there are no standards to define the effects of different types of brushes and bristles on various duct surfaces (NADCA, 1995). To the knowledge of the author, no literature is available on the theoretical modelling of duct cleaning brushes.

3 AIMS OF THE STUDY

The general objective of the study was to evaluate dust accumulation in, and removal from, recently installed supply air ducts and to develop a mathematical model for calculating the behaviour of a rotating cleaning brush in a duct.

The specific objectives of the study were:

- to find dust measuring methods suitable for evaluating the need for cleaning and for verifying the cleanliness of new air ducts upon completion of the cleaning work (I)

- to evaluate the effectiveness of protective measures, defined by (FiSIAQ, 2001), designed to ensure a clean supply air duct system in new installations and to find out the amount of dust accumulation in the various sections of the ductwork (II)

- to compare the efficiency of two dry air duct cleaning methods, i.e. mechanical brushing and compressed air cleaning, in new ducts and to find out the cleaning results of the studied methods for practical purposes (III)

- to develop a mathematical model to evaluate the bristle contact force and the contact angle in rotating brush duct cleaning and to compare the results of the simulation with those obtained in the laboratory tests (IV)

- to compare the results obtained by using two numerical integration methods – Simpson's integration rule with the results achieved by Lagrangian interpolation – and to compare the effect of the degree of the polynomial trial solution (V)

- to find out the effect of air drag on the bristle tip normal force and the contact angle and the needed torque, and to compare the results obtained in a laboratory test with the results of the simulation (VI).

4 LABORATORY AND FIELD STUDIES

The amount of dust was measured using the vacuum test method (II–III) defined in I. Additionally, two researchers estimated visually the appearance and the amount of dust at each sampling site (I–III). During visual inspection, the intensity and direction of the illumination were taken into account by using the same flashlight and the results recorded systematically on the visual inspection form (Holopainen et al., 2002). A 95% confidence interval (CI) was the level used in the significance tests that compared means (*T*-test) and variances (*F*-test) in I–III.

4.1 Comparison of dust measuring methods

The air handling systems in thirteen recently built or renovated buildings were selected randomly for the study in the Helsinki metropolitan area (I). The amount of dust was measured using the vacuum test method, the gravimetric tape method and the optical method. The parallel dust samples in each method were taken from the same location on the duct surface, at an approximate distance of 5 mm from each other. Each sampling site seemed visually to have the same amount of dust for all the measuring methods. Additionally, the homogeneity of the dust distribution was studied in a building under construction. The total number of dust sampling sites was 45.

4.2 Inspection of dustiness in newly installed air ducts

The air handling systems in eighteen recently built or renovated buildings were selected randomly for the study (II). The studied buildings were four day-care centres, two cinema centres, five office buildings and seven schools. The air handling systems of the buildings were installed between autumn 1998 and autumn 2000. In the construction specifications, attention was paid to the cleanliness of the air handling system. One day-care centre, four office buildings and four schools were constructed according to the cleanliness category P1. Two cinema centres, three day-care centres, one office and three schools were constructed according to category P2 with two specific instructions for installation: (1) ducts were to be protected with caps on the open ends during construction of three of the buildings, (2) ducts were to be cleaned after the construction phase in four of the buildings. In two of the buildings, no requirements were stated for the cleanliness of the ducts. In each building, 3–28 samples were taken, depending on the number of access openings and the total length of the ductwork of the air handling system. The total number of dust samples was 139.

4.3 Evaluation of duct cleaning methods

The mechanical brushing and the compressed air cleaning methods were tested in the laboratory with ASHRAE (1992) test dust and dust accumulated at the construction site and in the field (III). The professional duct cleaners selected the type of the brushes, the air nozzles or the air dusting gun as the aim was to achieve an acceptable cleaning result visually, i.e. repeated duct cleaning did not change the cleaning result and no loosened dust was detected visually on the duct surface after cleaning. The ducts were photographed before and after cleaning with a digital camera and the cleaning time was recorded. In both laboratory tests, oil residues of the metal ducts were measured using a filter contact method (Asikainen et al., 2003b).

4.3.1 Cleaning efficiency test with ASHRAE dust

The cleaning methods were tested in the laboratory with three different types of round air ducts: a metal duct without residual oil (<12 mg/m^2) (cleanliness category P1), a metal duct with residual oil (216–338 mg/m^2) (cleanliness category P2) and a plastic duct (III). The length of a 7.5 m ductwork consisted of three straight ducts connected to two pieces of 90° bends. The ductworks were contaminated with standard ASHRAE test dust (ASHRAE, 1992) (30 g) using a dust feeding device (Kovanen, 2000). The amount of dust was measured at five parallel sampling sites before and after cleaning. The speed of airflow that conveyed the dislodged dust from the duct was approximately 10 m/s before mechanical brushing (MB1–MB2) and 23–24 m/s before compressed air cleaning (CAC1). The test ductworks with the bends were cleaned once back and forth.

4.3.2 Laboratory test with dust accumulated at construction site

The cleaning methods were tested in two cleanliness categories round air ducts: a metal duct without residual oil (≤20 mg/m^2) (P1) and a metal duct with residual oil (<5–278 mg/m^2) (P2) (III). The length of a 20 m ductwork consisted of three straight ducts connected to two pieces of 180° bends. The ducts were transported directly from the manufacturer to two different construction sites where they were kept unprotected with open ends for two to three weeks to allow them to become contaminated. After the storage period, the ducts were sealed and transported to the laboratory. The amount of dust was measured at six parallel sampling sites before and after cleaning. The speed of airflow was approximately 15 m/s before both mechanical brushing (MB3–MB6) and compressed air cleaning (CAC2). Only the straight parts of the ductworks were cleaned once back and forth.

4.3.3 Field measurements

Three school buildings and two office buildings under construction were selected randomly for the study in the Helsinki metropolitan area (III). The total length of ductwork was approximately 5500 m cleaned with the mechanical brushing (MB7–MB10) method and 20 m cleaned with the compressed air cleaning (CAC3) method. The ducts were mostly round air ducts and manufactured according to cleanliness category P1. The amount of dust was measured from 32 sampling sites before and after cleaning. Before mechanical brushing, the professional duct cleaners used their experience to adjust the speed of airflow in the ducts with dampers to such a level that the airflow conveyed the dislodged dust out of the ducts into the filter unit. In the compressed air cleaning, dust was blown out of two separate straight ducts into the surrounding space by the air dusting gun without a vacuum collector. In both cleaning methods, the ducts were cleaned so many times that acceptable cleaning results were achieved visually.

5 MODEL OF DUCT CLEANING BRUSH

5.1 Introduction

Mechanical brushing with rotating brushes is an efficient and commonly used method of cleaning metal round air ducts, which are used particularly in Scandinavian countries. The rotating duct cleaning brushes are normally designed using empirical knowledge. Without a theoretical model, however, it is difficult to estimate the dependence of various parameters on the behaviour of a rotating bristle and the cleaning efficiency of a brush.

Considering the deposit particles on the duct surface, it seems more or less clear that the larger the normal force N and the smaller the contact angle β, the better the cleaning efficiency (Figure 5.1). However, it is recognised that other factors such as the detailed geometric shape of the possibly worn bristle tip, the surface pressure, and the sweeping speed may also have a significant affect on cleaning efficiency.

In IV−VI, the model to simulate the behaviour of a bristle of a rotating duct cleaning brush was developed. The main interest was to determinate the normal force and the contact angle in terms of parameters of the problem such as the angular speed of the brush ω and the ratio L/R etc. The results of the simulation were compared with those obtained from a laboratory test.

Figure 5.1 (a) shows schematically the deformed shape of a typical rotating bristle in a duct and the forces acting at the bristle tip. Figure 5.1 (b) shows in more detail a possible sweeping action at the bristle tip.

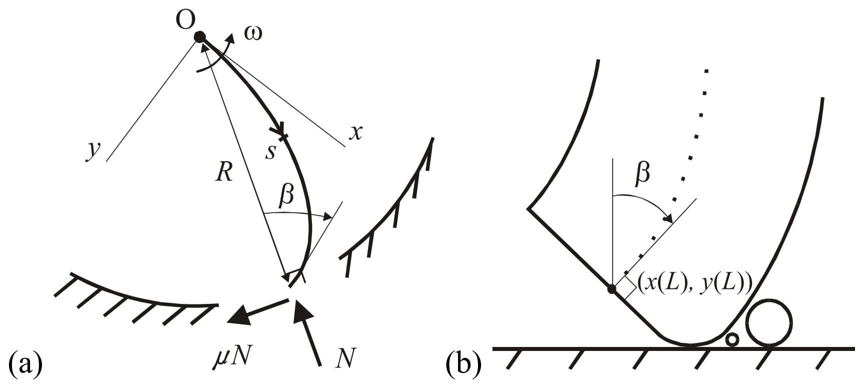


Figure 5.1. (a) Deformed bristle and the contact forces at the bristle tip. (b) Bristle tip and some dust particles.

5.2 Modelling bristle behaviour

The bristle is modelled using large deformation elastic theory (IV−VI). Certain simplifying assumptions are made. (1) Plane steady motion of an initially straight uniform bristle is assumed. (2) Zero size for the attaching frame is used. (3) The effect of gravity on the bristle is assumed to be ignored. The order of the magnitude of the ratio ($2g/\omega^2 R$) between the gravity of the bristle (mg) and the resulting approximate centrifugal force ($m\omega^2 R/2$) is below 0.2 using practical data. (4) The bristle is considered to obey elastic rod theory so that the deformations are due to the bending moment only and the deformations due to beam normal force and shearing force are considered to be ignored. This is well justified considering the slenderness of the bristles. (5) The contact forces and contact are assumed to take place at the central axis of the bristle tip; this may lead to a small error (Figure 5.1 (b)).

Figure 5.2. describes the setting in some detail. The study of the bristle behaviour is performed in a xy-coordinate system with its origin at the rotation centre O and rotating with the attached frame. The x-axis is along the undeformed straight bristle axis and the y-axis is 90 degrees in the clockwise direction according to the usual convention in strength of materials; see, for example, (Timoshenko and Gere, 1961). In this frame, the bristle is assumed to be in a static state and the motion is taken into account in the usual manner via centrifugal forces.

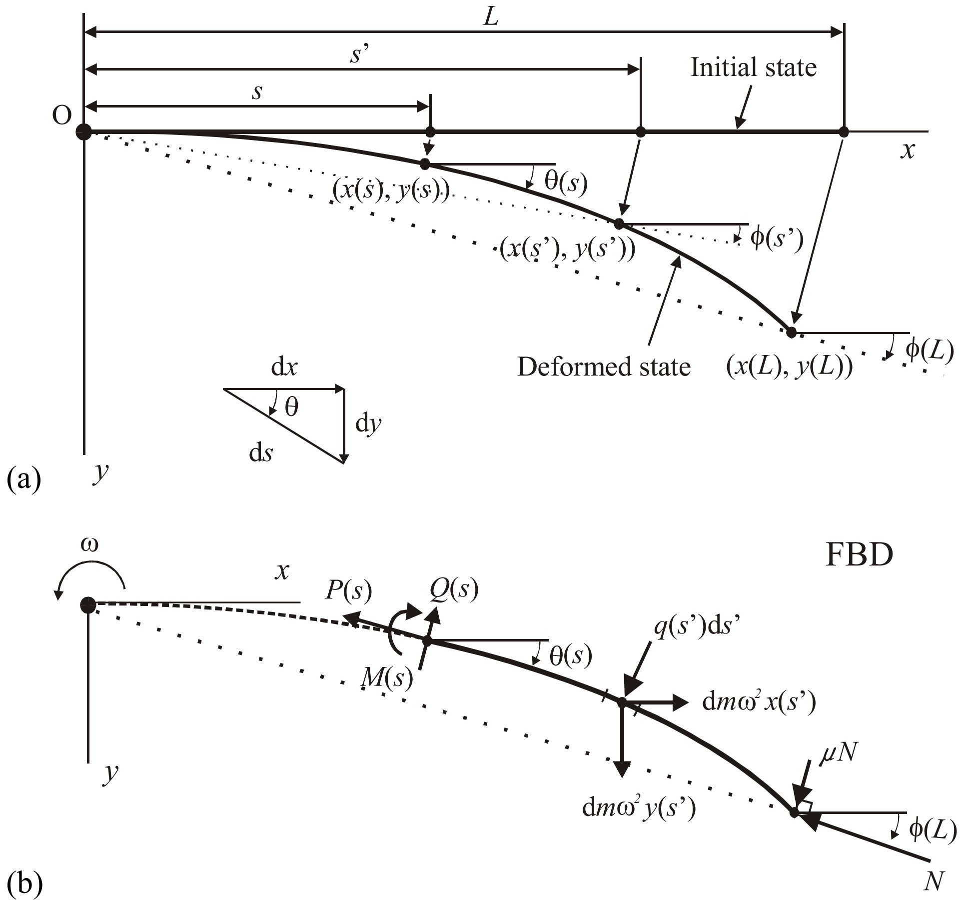


Figure 5.2. (a) Large deflection of a deformed bristle and (b) a free-body diagram.

The exact differential equation of the deflection curve is (Timoshenko and Gere, 1961)

$$M = -EI\frac{\mathrm{d}\theta}{\mathrm{d}s}. \tag{5.1}$$

Further, the shearing force Q is connected to the bending moment by $Q = \mathrm{d}M/\mathrm{d}s$ and thus with constant EI:

$$Q = -EI\frac{\mathrm{d}^2\theta}{\mathrm{d}s^2}. \tag{5.2}$$

Figure 5.2 (a) shows the free-body diagram of an end part of the bristle. In addition to the bending moment M and shearing force Q, the rod normal force P at the generic rod cross-section is shown. A differential rod length element $\mathrm{d}s'$ has mass $\mathrm{d}m = \rho_\mathrm{b} A\mathrm{d}s'$ where ρ_b is the density and A its cross-sectional area of the bristle. The centrifugal force components acting on mass element $\mathrm{d}m$ in the x- and y-directions are $\mathrm{d}m\omega^2 x(s')$ and $\mathrm{d}m\omega^2 y(s')$, respectively. The notation s' is used for an arc length coordinate referring to a generic point inside the end part of the bristle to differentiate it from the arc length coordinates referring to a generic cross-sectional point. Air drag is assumed to act perpendicular to the bristle axis. We thus ignore the possible axial component of the drag. Denoting the intensity by q ($[\mathrm{q}]=\mathrm{N/m}$), the force acting on $\mathrm{d}s'$ is in magnitude $q(s')\mathrm{d}s'$. The inclination angle $\phi(L)$ at the bristle tip associated with the contact normal force N is fixed here due to the fact that the line of the action of the contact normal force N goes through the duct centre and thus, here, also through the rotation centre O. Assuming Coulomb friction, we obtain the friction force μN acting perpendicular to the contact normal force N. The governing field equation (5.2) becomes (IV)

$$\begin{aligned} &N[\sin\theta(s)\cos\phi(L) - \cos\theta(s)\sin\phi(L)] + \mu N[\cos\theta(s)\cos\phi(L) + \sin\theta(s)\sin\phi(L)] \\ &- \rho_\mathrm{b} A\omega^2 \sin\theta(s)\int_s^L x(s')\mathrm{d}s' + \rho_\mathrm{b} A\omega^2 \cos\theta(s)\int_s^L y(\mathrm{s}')\mathrm{d}s' \\ &+ \cos\theta(s)\int_s^L \cos\theta(s')q(s')\mathrm{d}s' + \sin\theta(s)\int_s^L \sin\theta(s')q(s')\mathrm{d}s' = -EI\frac{\mathrm{d}^2\theta}{\mathrm{d}s^2}. \end{aligned} \tag{5.3}$$

The boundary conditions are as follows: The bending moment must vanish at the bristle tip. This gives

$$\frac{\mathrm{d}\theta}{\mathrm{d}s}(L) = 0. \tag{5.4}$$

Further, at the origin the bristle axis is at a tangent to the x-axis:

$$\theta(0) = 0. \tag{5.5}$$

The geometrical condition is as follows: The bristle tip with coordinates $x(L)$ and $y(L)$ is on the duct surface, i.e. its distance from the origin is R:

$$\sqrt{x^2(L)+y^2(L)} = R\,. \tag{5.6}$$

The problem to be solved is described by the field equation (5.3) and the boundary conditions (5.4) and (5.5). Additionally, there is the geometric constraint condition (5.6). The corresponding unknowns to be determined are the function $\theta = \theta(s)$ and the constant N.

Further relations needed above are:

$$x(s) = \int_0^s \cos\theta(s')\,\mathrm{d}s'\,, \tag{5.7}$$

$$y(s) = \int_0^s \sin\theta(s')\,\mathrm{d}s' \tag{5.8}$$

and from Figure 5.2 (a)

$$\cos\phi(L) = \frac{x(L)}{R}\,, \tag{5.9}$$

$$\sin\phi(L) = \frac{y(L)}{R}\,. \tag{5.10}$$

The standard form of magnitude of the air drag per unit length for a cylinder with circular cross-section is (Schlichting, 1979)

$$q_\mathrm{N} = \frac{1}{2} C_\mathrm{D} \rho_\mathrm{a} v^2 d\,, \tag{5.11}$$

where C_D is the air drag coefficient, ρ_a the density of air, v the speed of the cylinder with respect to air and d the diameter of the cylinder. The drag coefficient depends on the Reynolds number

$$\mathrm{Re} = \frac{vd}{\nu_\mathrm{a}}\,, \tag{5.12}$$

where ν_a is the kinematic viscosity of the air. The speed of a bristle point with respect to stagnant air is $\omega\, r(s')$, where

$$r(s') = \sqrt{x^2(s') + y^2(s')} \tag{5.13}$$

is the radial distance from the origin. The brush certainly sets the surrounding air into motion, which is difficult to estimate. In an effort to take this into account, we evaluate the speed by

$$v = c\omega\, r(s'), \tag{5.14}$$

where c is a dimensionless multiplier ($0 < c \leq 1$). If some experimental results are available, c can hopefully be made use of. According to (Blevins, 1990), when the flow is inclined to the axis of a cylinder, the air drag intensity normal to the axis can be evaluated from

$$q = q_{\mathrm{N}} \cos^2 \gamma\,, \tag{5.15}$$

where

$$\gamma(s') = \theta(s') - \phi(s') \tag{5.16}$$

is here the angle between the rod normal and rod velocity vector. In IV and VI, the formulation of air drag is described in more detail.

5.3 Solution methods

The continuous problem consisting of the determination of the unknown $\theta = \theta(s)$ and N described in the previous chapter cannot be solved analytically. The point collocation method with a trial solution consisting of undetermined parameters was employed to obtain an approximate discrete solution. The unknown function $\theta = \theta(s)$ was approximated by a trial solution

$$\theta(s) \approx \tilde{\theta}(s) = \sum_{i=0}^{n} c_i s^i = c_0 + c_1 s + c_2 s^2 + c_3 s^3 + \ldots + c_n s^n\,, \tag{5.17}$$

where $c_0, c_1, \ldots, c_n$ are undetermined parameters and the given basis functions are simply powers of s. The normal force $\tilde{N}$ is an additional discrete unknown so the total number of unknowns is $n+2$.

The discrete equations following from (5.3) using collocation are

$$\tilde{N}\left[\sin\tilde{\theta}(s_k)\frac{\tilde{x}(L)}{R} - \cos\tilde{\theta}(s_k)\frac{\tilde{y}(L)}{R}\right] + \mu\tilde{N}\left[\cos\tilde{\theta}(s_k)\frac{\tilde{x}(L)}{R} + \sin\tilde{\theta}(s_k)\frac{\tilde{y}(L)}{R}\right]$$

$$-\rho_{\mathrm{b}} A\omega^2 \sin\tilde{\theta}(s_k)\int_{s_k}^{L}\tilde{x}(s')\,\mathrm{d}s' + \rho_{\mathrm{b}} A\omega^2 \cos\tilde{\theta}(s_k)\int_{s_k}^{L}\tilde{y}(s')\,\mathrm{d}s'$$

$$+\cos\tilde{\theta}(s_k)\int_{s_k}^{L}\cos\tilde{\theta}(s')q(s')\mathrm{d}s' + \sin\tilde{\theta}(s_k)\int_{s_k}^{L}\sin\tilde{\theta}(s')q(s')\mathrm{d}s'$$

$$= -EI\frac{\mathrm{d}^2\tilde{\theta}}{\mathrm{d}s^2}(s_k), \qquad k = 1,\ldots,n-1. \tag{5.18}$$

The collocation points are taken uniformly with the endpoints included, as is shown in Figure 5.3. The remaining three equations are obtained from (5.4), (5.5) and (5.6).

Condition (5.5) leads to

$$\tilde{\theta}(0) = c_0 = 0. \tag{5.19}$$

The discrete boundary condition at the bristle tip (5.4) is

$$\frac{\mathrm{d}\tilde{\theta}}{\mathrm{d}s}(L) = c_1 + 2c_2 L + 3c_3 L^2 + \ldots + nc_n L^{n-1} = 0. \tag{5.20}$$

The geometrical condition (5.6) takes the form

$$\sqrt{\tilde{x}^2(L) + \tilde{y}^2(L)} = R. \tag{5.21}$$

The resulting set of $n+2$ non-linear algebraic equations was solved by the Find command in Mathcad (2003).

The evaluation of the integrands in (5.18) due to the centrifugal forces is considered in more detail below. The equivalents of formulas (5.7) and (5.8) are

$$\tilde{x}(s) = \int_0^s \cos\tilde{\theta}(s')\mathrm{d}s', \tag{5.22}$$

$$\tilde{y}(s) = \int_0^s \sin\tilde{\theta}(s')\mathrm{d}s'. \tag{5.23}$$

The integrals were calculated by two different numerical methods. In IV and VI, Lagrangian interpolation (Burden and Faires, 1993) is applied as follows:

$$\cos\left[\tilde{\theta}(s')\right] \approx \sum_{j=1}^{m} L_j(s')\cos\tilde{\theta}(s_j'), \tag{5.24}$$

$$\sin\left[\tilde{\theta}(s')\right] \approx \sum_{j=1}^{m} L_j(s')\sin\tilde{\theta}(s_j'), \tag{5.25}$$

where $L_j(s')$ are Lagrangian interpolation functions and the coordinates s_j' refer to the interpolation points. The cosines and sines are evaluated from

$$\cos\left[\tilde{\theta}\left(s_j^{'}\right)\right] \approx \cos\left[c_0 + c_1 s_j^{'} + c_2\left(s_j^{'}\right)^2 + c_3\left(s_j^{'}\right)^3 + \ldots + c_n\left(s_j^{'}\right)^n\right], \tag{5.26}$$

$$\sin\left[\tilde{\theta}\left(s_j^{'}\right)\right] \approx \sin\left[c_0 + c_1 s_j^{'} + c_2\left(s_j^{'}\right)^2 + c_3\left(s_j^{'}\right)^3 + \ldots + c_n\left(s_j^{'}\right)^n\right]. \tag{5.27}$$

The integrands are now polynomials and can be integrated analytically to give

$$\tilde{x}(s) = \sum_{j=1}^{m} M_j(s)\cos\left[\tilde{\theta}\left(s_j\right)\right], \tag{5.28}$$

$$\tilde{y}(s) = \sum_{j=1}^{m} M_j(s)\sin\left[\tilde{\theta}\left(s_j\right)\right], \tag{5.29}$$

where

$$M_j(s) = \int_0^s L_j(s')\,\mathrm{d}s'. \tag{5.30}$$

The values $n = 6$ and $m = 4$ were employed in IV and VI. A further similar integration is performed to evaluate the final centrifugal terms (IV).

Simpson's integration rule is applied as an alternative numerical method in V. Employing collocation, the integrals in (5.3) are needed only with certain fixed lower limits. Using a uniform distribution of collocation points also makes the application of Simpson's rule straightforward, as the step length used in it becomes a constant.

Three cases with different degrees of approximation are considered.

Case 1 ($n = 4$):

$$\tilde{\theta}(s) = c_0 + c_1 s + c_2 s^2 + c_3 s^3 + c_4 s^4. \tag{5.31}$$

Case 2 ($n = 6$):

$$\tilde{\theta}(s) = c_0 + c_1 s + c_2 s^2 + c_3 s^3 + c_4 s^4 + c_5 s^5 + c_6 s^6. \tag{5.32}$$

Case 3 ($n = 8$):

$$\tilde{\theta}(s) = c_0 + c_1 s + c_2 s^2 + c_3 s^3 + c_4 s^4 + c_5 s^5 + c_6 s^6 + c_7 s^7 + c_8 s^8. \tag{5.33}$$

The collocation points used are shown in Figure 5.3.

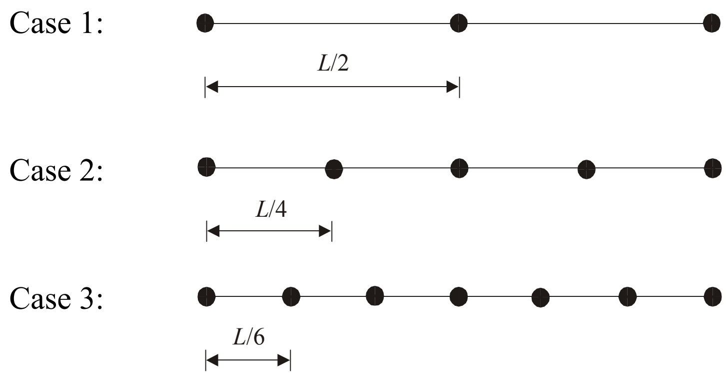


Figure 5.3. Collocation points.

The minimum number of integration points for the convenient evaluation of the final integrals is, for cases 1, 2 and 3 respectively, 9, 17 and 25. This is because in Simpson's rule

$$\int_a^b f(x)\,\mathrm{d}x \approx \frac{b-a}{6}\left[f(a)+4f\left(\frac{a+b}{2}\right)+f(b)\right]. \tag{5.34}$$

The "midvalues" at $(a+b)/2$ in an interval $b-a$ with step lengths $(b-a)/2$ also need to be evaluated, although the value of the integral at the midpoints is not obtained. As there are in fact two consecutive integrals, this means that we have to divide the lengths $L/2$, $L/4$ and $L/6$ in Figure 5.3 into at least four step lengths. Describing this in the following by the evaluation of

$$\int_{s_k}^{L} x(s')\,\mathrm{d}s'\,. \tag{5.35}$$

The evaluation of

$$\int_{s_k}^{L} y(s')\,\mathrm{d}s' \tag{5.36}$$

proceeds similarly.

In describing the procedure, the minimum number of integration points is employed for the sake of simplicity. The situation in relation to case 1 is explained in more detail (Figure 5.4). The first integration is

$$\tilde{x}\left(s_j'\right)=\int_0^{s_j'}\cos\tilde{\theta}\left(s^*\right)\mathrm{d}s^* \tag{5.37}$$

at the nine integration points $s_1^*=0$, $s_2^*=L/8$, $s_3^*=L/4,\ldots,$ $s_9^*=L$.

Equation (5.34) is applied in a piecewise manner with $f(x)$ replaced by $\cos\tilde{\theta}(s^*)$. At the integration points

$$\cos\tilde{\theta}(s_i^*) \approx \cos\left(c_0 + c_1 s_i^* + c_2 (s_i^*)^2 + c_3 (s_i^*)^3 + c_4 (s_i^*)^4\right),\ i = 1, 2, ..., 9. \tag{5.38}$$

(a) (b) (c)

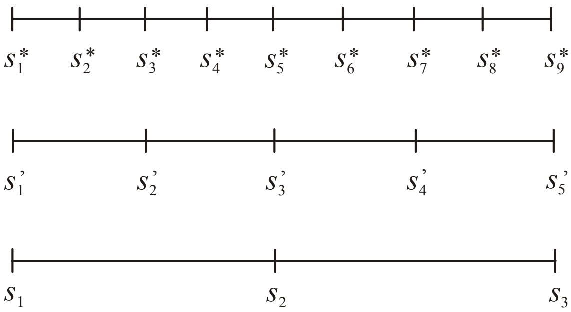


Figure 5.4. (a) Integration points s_i^* to obtain $\tilde{x}(s_j')$ at the next integration points s_j' shown in Figure (b). (b) Integration points s_j' to obtain $I_x(s_k)$ at the collocation points s_k shown in Figure (c).

The value of $\tilde{x}(s_j)$ is determined at the next integration points $s_1' = 0$, $s_2' = L/4$, $s_3' = 2L/4$, $s_4' = 3L/4$, $s_5' = 4L/4$.

Denoting first

$$I_x(s_k) = \int_0^{s_k} x(s')\,\mathrm{d}s' \tag{5.39}$$

we obtain

$$\int_{s_1}^{L} x(s')\,\mathrm{d}s' = \tilde{I}_x(s_3) - \tilde{I}_x(s_1) = \tilde{I}_x(s_3), \tag{5.40}$$

$$\int_{s_2}^{L} x(s')\,\mathrm{d}s' = \tilde{I}_x(s_3) - \tilde{I}_x(s_2), \tag{5.41}$$

$$\int_{s_3}^{L} x(s')\,\mathrm{d}s' = \tilde{I}_x(s_3) - \tilde{I}_x(s_3) = 0\,. \tag{5.42}$$

5.4 Solution details

The non-linear algebraic system consisting of the $n+2$ equations (5.18), (5.19), (5.20) and (5.21) was coded and solved by Mathcad software. The program needs an initial guess for the unknown to proceed. The initial values were taken to be, $c_0 = 0$, $c_1 = 0.5/L$, $c_2 = -0.25/L^2$, $c_3 = c_4 = c_5 = c_6 = 0$ and $\widetilde{N} = 0$. Parameter c_0 was not actually included in the code. The non-zero values were estimated making some use of equations (5.4) and (5.8). The stop condition, i.e. convergence (TOL) and the constraint tolerances ($CTOL$), was 0.001 for a solution to be acceptable. The flow chart of the numerical solution is presented in Figure 5.5.

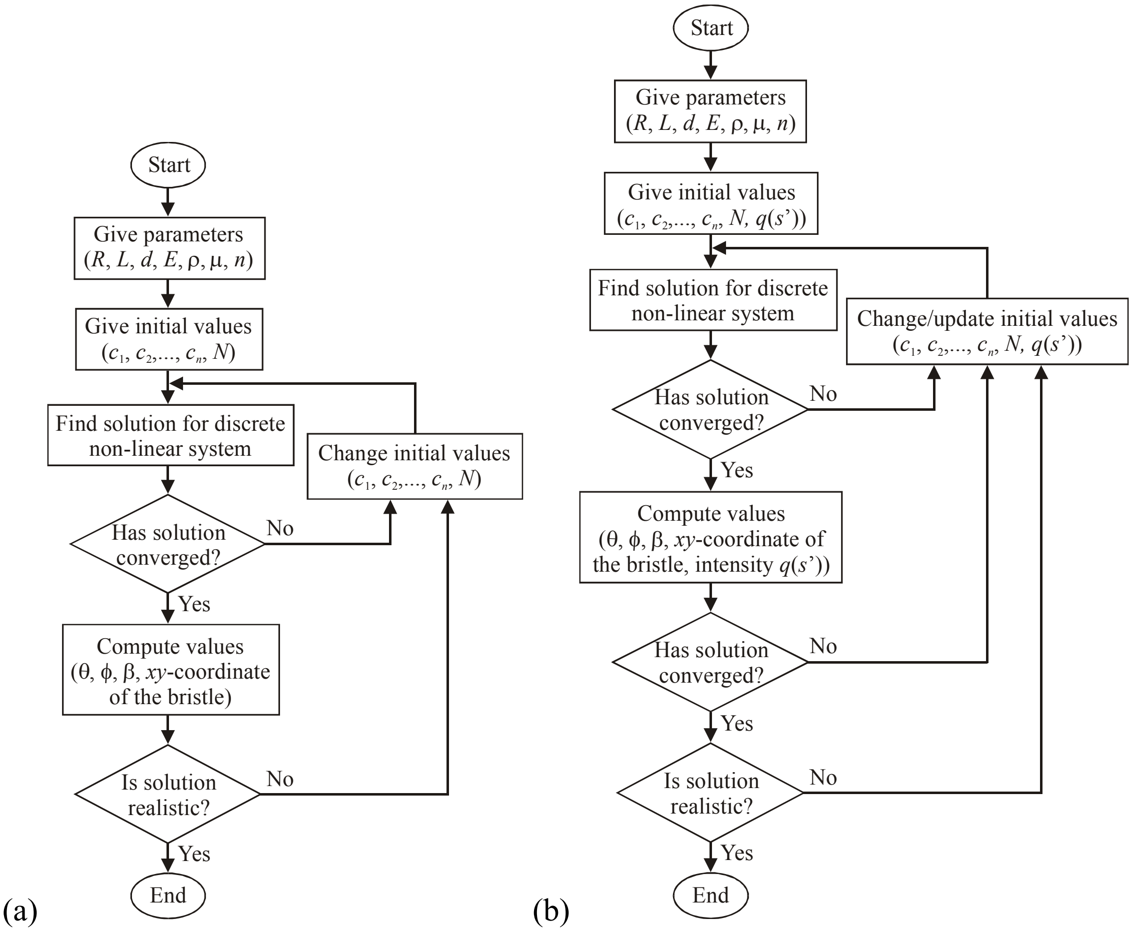


Figure 5.5. Schematic flow chart for numerical solution of brush model. (a) Without air drag, (b) with air drag.

With regard to the integrals in equation (5.18), the terms due to centrifugal forces have been evaluated "directly" according to Figure 5.5 (a). However, the terms from air drag are so complicated that a direct approach is out of the question. Thus $q(s')$ is updated iteratively according to the current achieved shape ($c_0, c_1, ..., c_n$) of the bristle (Figure 5.5 (b)). The integrands $\cos\widetilde{\theta}(s')q(s')$ and $\sin\widetilde{\theta}(s')q(s')$ are then represented by the Lagrangian interpolation functions and integrated analytically. This is an "indirect" approach, which actually could also be used for the centrifugal forces. On average, three iterations were needed to achieve practically converged results (VI and VI).

To get some idea of the accuracy of the discrete solution methods, a somewhat similar problem to the present one – the famous Elastica problem described in (Timoshenko and

Gere, 1961) − with a known analytical solution was studied using the simulation model in V.

5.5 Dimensionless formulation

To simplify the study of the dependencies between the various quantities, a dimensionless formulation is employed. The final purpose of implementing the dimensionless formulation is to make the eventual future design process as systematic as possible. As is mentioned in (Crandall, 1956): "This is an extremely useful organizational tool of the analyst. In connection with numerical simulations it removes all unnecessary symbols, leaving the basic problem in its simplest form."

From the governing dimensionless formulation consisting of the field equation and boundary conditions, it was found that the solution $\overline{\theta}(\xi)$, $\overline{N}$, where $\overline{\theta}(\xi) \equiv \theta(s(\xi))$ and a dimensionless normal force $\overline{N} = 64L^2 N / \pi E d^4$, depends on five dimensionless numbers (IV):

$$\pi_1 = \frac{\rho_b A \omega^2 L^4}{EI}, \tag{5.43}$$

$$\pi_2 = \frac{L}{R}, \tag{5.44}$$

$$\pi_3 = \mu, \tag{5.45}$$

$$\pi_4 = \frac{c^2 \rho_a \omega^2 L^5 d}{EI}, \tag{5.46}$$

$$\pi_5 = \frac{c\omega Ld}{\nu_a}. \tag{5.47}$$

5.6 Verification of the model

A rotating brush was tested in the laboratory. A round duct with a diameter $2R = 0.315$ m was prepared from a metal sheet plate with a width of 0.2 m. The diameter $2L$ of the tested nylon brush was 0.35 m with a bristle thickness d of 1×10^{-3} m. The bristles were connected to a spiral frame made of metal wire. The number of bristles n was approximately 1000. The brush was centralized at the centre of the duct with the shaft of an electric motor (0.55 kW). Additionally, certain tests were performed with just a single pair of bristles. Figure 5.6 presents some details of the instrumentation of the laboratory test (IV and IV).

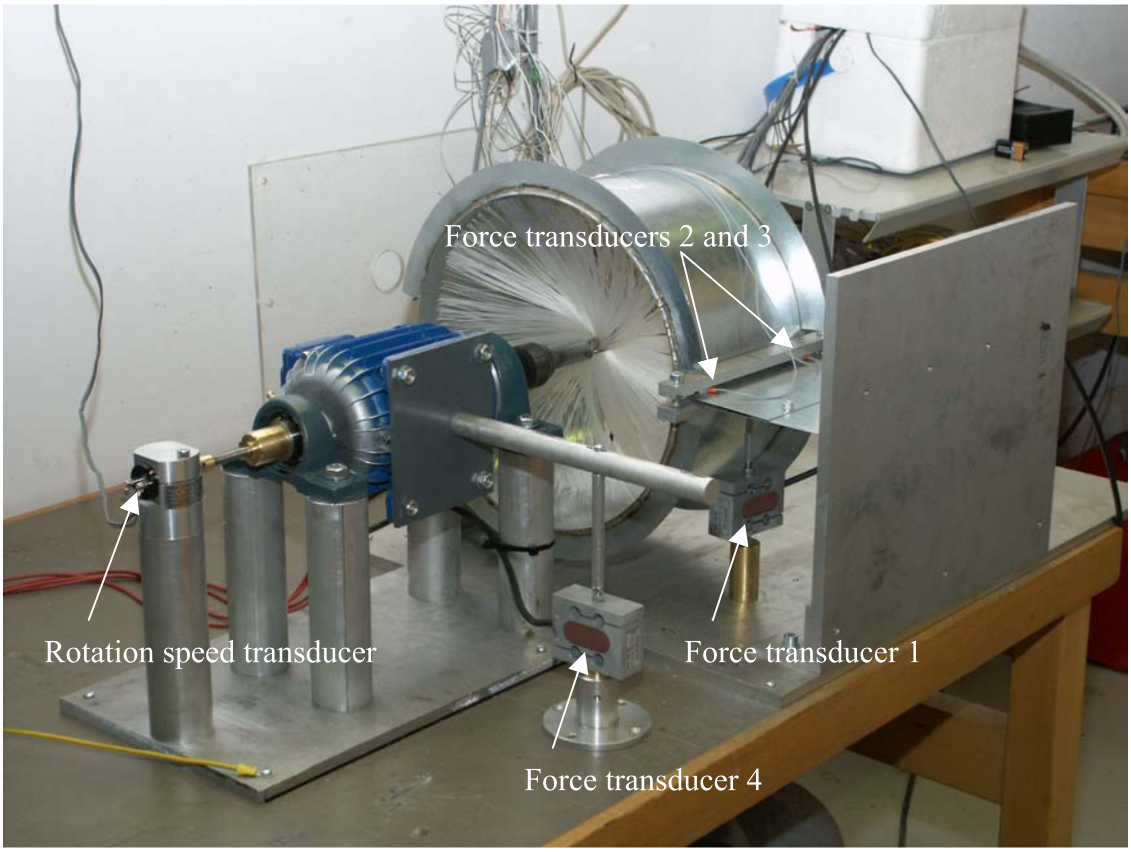
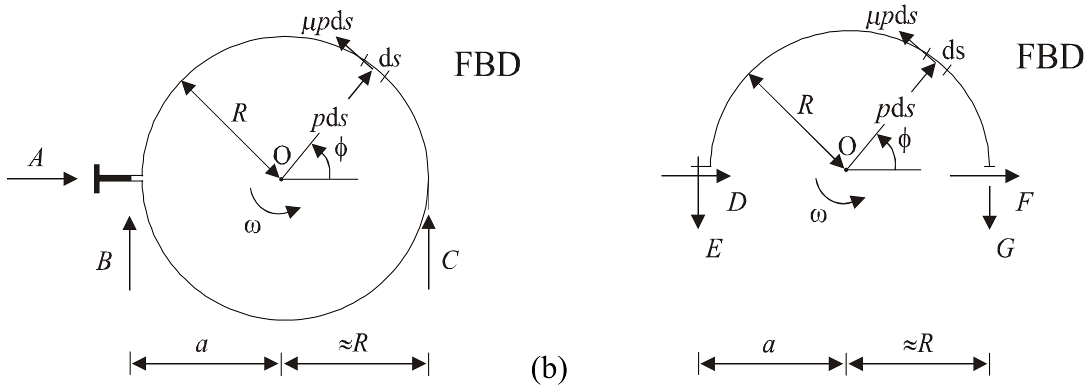


Figure 5.6. Experimental arrangement in the laboratory.

Measurements were obtained using force transducers 1, 2, 3 and 4. The range of transducers 1 and 4 was 0−118 N and of transducers 2 and 3 0−29 N. The transducers were located as indicated in Figure 5.6. The purposes of transducers 1 and 4 were to determine the torque (twisting moment) from the contact friction and the output torque from the electric motor, respectively. The purpose of transducers 2 and 3 was to additionally measure the "opening force" in the seam of the duct frame.

Two free-body diagrams of the duct frame used in the analysis of the measurement results are shown in Figure 5.7. The direction from which the frame is viewed is the opposite of that of the motor in Figure 5.6. The rotation direction of the motor and the brush shown in the diagrams is referred to here and in the following text as counterclockwise.



(a) (b)

Figure 5.7. (a) Free-body diagram of the frame. (b) Free-body diagram of the upper part of the frame.

The output torque T from the motor is considered to be balanced in general by the torque T_{bf}, due to the bearing friction (some possible air drag acting on the shaft is included), by the torque T_{ad}, due to the air drag from the brush (or from a bristle pair) and by the torque T_{μ}, due to the contact friction of the brush (or of a bristle pair) with the duct surface; thus in general $T = T_{\mathrm{bf}} + T_{\mathrm{ad}} + T_{\mu}$.

The torque required to resist the contact friction from the motor (force transducer 4) is

$$T_{\mu} = T - \left(T_{\mathrm{ad}} + T_{\mathrm{bf}}\right) = \mu n N R . \tag{5.48}$$

Alternatively, using the measured value for B (from force transducer 1)

$$T_{\mu} = B(a + R). \tag{5.49}$$

When the brush (or a bristle pair) is rotated in air, the torque due to air drag (determined from $T = T_{\mathrm{bf}} + T_{\mathrm{ad}}$, assuming T_{bf} known) is

$$T_{\mathrm{ad}} = T - T_{\mathrm{bf}} . \tag{5.50}$$

Additionally, the brush was rotated without contact in a duct with a diameter of 0.365 m to find the possible effect of bulk air motion on the torque due to air drag.

The bristle contact normal force N and the coefficient of friction μ using the measured data are found to be (the value of E is measured from the force transducers 2 and 3)

$$N = \left(\frac{a}{R} + 1\right)\left(\frac{B}{2} + E\right)\frac{\pi}{n}, \tag{5.51}$$

$$\mu = \frac{1}{\left(\frac{1}{2} + \frac{E}{B}\right)\pi} . \tag{5.52}$$

The simulations performed above are based on the assumption that the rotation direction of the brush is counterclockwise. If the rotation direction is changed, formulas (5.51) and (5.52) change to

$$N' = \left(\frac{a}{R} + 1\right)\left(\frac{B'}{2} + E'\right)\frac{\pi}{n}, \tag{5.53}$$

$$\mu' = -\frac{1}{\left(\frac{1}{2} + \frac{E'}{B'}\right)\pi}. \tag{5.54}$$

6 RESULTS

6.1 Comparison of dust measuring methods

The average surface dust level determined by the vacuum test method in thirteen recently built buildings was 1.3 g/m^2 (<0.1−8.4 g/m^2) (I). The gravimetric tape method gave slightly lower mean results 1.2 g/m^2 (<0.1−5.0 g/m^2) than the vacuum test method. The optical method gave cleanliness results of 15% (2−41%). The relative standard deviations (RSD) of the parallel samples were higher in the gravimetric tape method than in the optical method. However, the quality of the dust affected the performance of the optical methods. Out of 180 samples, the optical measuring device gave 12 zero readings. In some of these cases, the device gave a zero reading even though dust spots were visually observed on the tape.

The highest mean amount of dust sampled from ten parallel sampling sites was 0.5 g/m^2 (0.1−1.0 g/m^2) collected with the vacuum test method (weighed with the field balance) and 0.4 g/m^2 (0.1−1.0 g/m^2) (weighed with the laboratory balance). The mean amount of dust with the gravimetric tape method was 0.4 g/m^2 (0.1−0.6 g/m^2) (weighed with the field balance). The result of the optical method was, on average, 9% (2−16%). The average wall loss of the suction hose in the vacuum test method was 0.1 g/m^2 (weighed with the field balance). The relative collection efficiency (RCE) for the gravimetric tape method was 0.8 compared with the vacuum test method. The means (*T*-test) and variances (*F*-test) of the parallel sampling sites measured with the vacuum test and the tape method (weighed with the field balance) did not differ significantly.

The linear multiple correlation coefficient (R^2) between the gravimetric tape method and the vacuum test method was 0.3. No linear correlation existed between the optical method and the vacuum test method ($R^2 < 0.1$). The linear multiple linear correlation coefficient between the optical method and the gravimetric tape method was 0.3. The obtained linear fitting function is

$$A_{\mathrm{fit}} = 6.49W_{\mathrm{t}} + 9.41\,, \tag{6.1}$$

where A_{fit} is the fitted value (%) of the optical method and W_{t} is the measured value (g/m^2) of the gravimetric tape method. A 95% confidence interval (CI) on the fitting line (6.1) is given in Figure 6.1 (a), where $\mathrm{CI}_{\mathrm{up}}$ is the upper confidence limit for the line and $\mathrm{CI}_{\mathrm{lo}}$ the lower limit.

Fransson et al. (1995) have presented a linear fitting function

$$A_{\mathrm{fitF}} = 11.25W_{\mathrm{t}} + 3.49 \tag{6.2}$$

between the optical method and the gravimetric method. Equations (6.1) and (6.2) give approximately the same value (17%) when the amount of dust accumulation is 1.2 g/m^2

using the gravimetric tape method (W_t). In Figure 6.1 (b), the particle overlap is taken into account in equation (6.1) using the formulation (Schneider et al., 1996)

$$A_t = -100 \ln\left(1 - \frac{A_{fit}}{100}\right), \tag{6.3}$$

where A_t is the corrected value (%) and A_{fit} the fitted value (%).

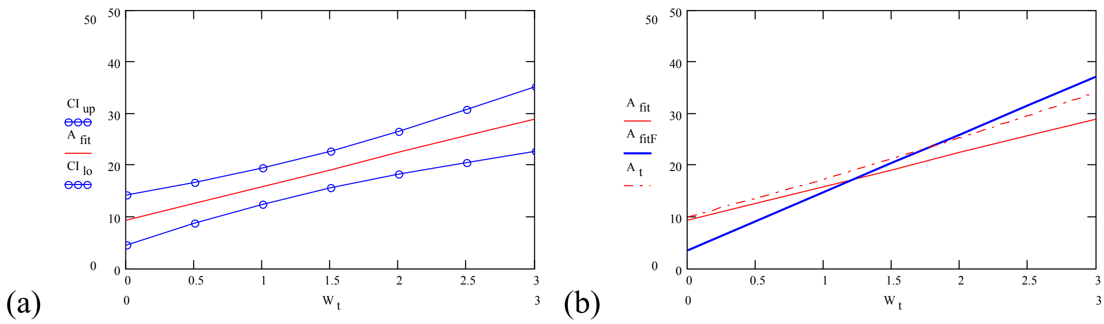


Figure 6.1. (a) 95% confidence band on A_{fit} (6.1). (b) Cleanliness level of optical method A_{fit} (6.1), A_{fitF} (6.2) and A_t (6.3) (%) as a function of result of gravimetric tape method W_t (g/m^2).

6.2 Amount of dust accumulation in newly installed supply air ducts

In the field measurements, the mean amount of accumulated dust was 0.9 g/m^2 (0.4–2.9 g/m^2) in category P1 ducts (II). In one case, the protection of the ducts was unsuccessful and the amount of dust was so high (2.9 g/m^2) that the ducts had to be cleaned after the construction process. When the samples of this building were not included in the results, the mean amount of dust was 0.7 g/m^2 (0.4–0.9 g/m^2) in the category P1 ducts. The average dust accumulation was almost the same as the set limit value in category P1 (1.0 g/m^2) defined by FiSIAQ (2001). Omitting the samples from the building where the protection against dust was unsuccessful, the highest mean amount of dust was 0.8 g/m^2 in the middle of the ducts and the lowest (0.5 g/m^2) near the air handling units. Additionally, the mean amount of dust was higher (1.5 g/m^2) in the round ducts than in the rectangular ducts (0.7 g/m^2).

In category P2 ducts, the mean amount of accumulated dust was 2.3 g/m^2 (1.2–4.9 g/m^2). The lowest dust load was 1.7 g/m^2 (1.3–1.9 g/m^2) in the ducts that were protected during construction work, whereas the highest mean amount of dust was 2.8 g/m^2 (1.2–4.9 g/m^2) in the ducts that were to be cleaned after installation. In the P2 ducts, the mean amount of dust was significantly higher ($P < 0.008$) than in the P1 ducts. However, the average amount of accumulated dust of all P2 installations met the limit value in cleanliness category P2 (2.5 g/m^2). On the other hand, the mean amount of dust was higher than 1.0 g/m^2 in all categories of P2 ducts. The highest mean amount of accumulated dust (3.3 g/m²) was found in the middle of the ducts and the lowest

(0.6 g/m^2) near the air handling units. In the round ducts, the mean amount of dust was 4.1 g/m^2, which was almost threefold the amount in the category P2 rectangular ducts (1.5 g/m^2).

The amount of accumulated dust in the new supply air ducts, together with present limit values (FiSIAQ, 2001), is shown in Figure 6.2.

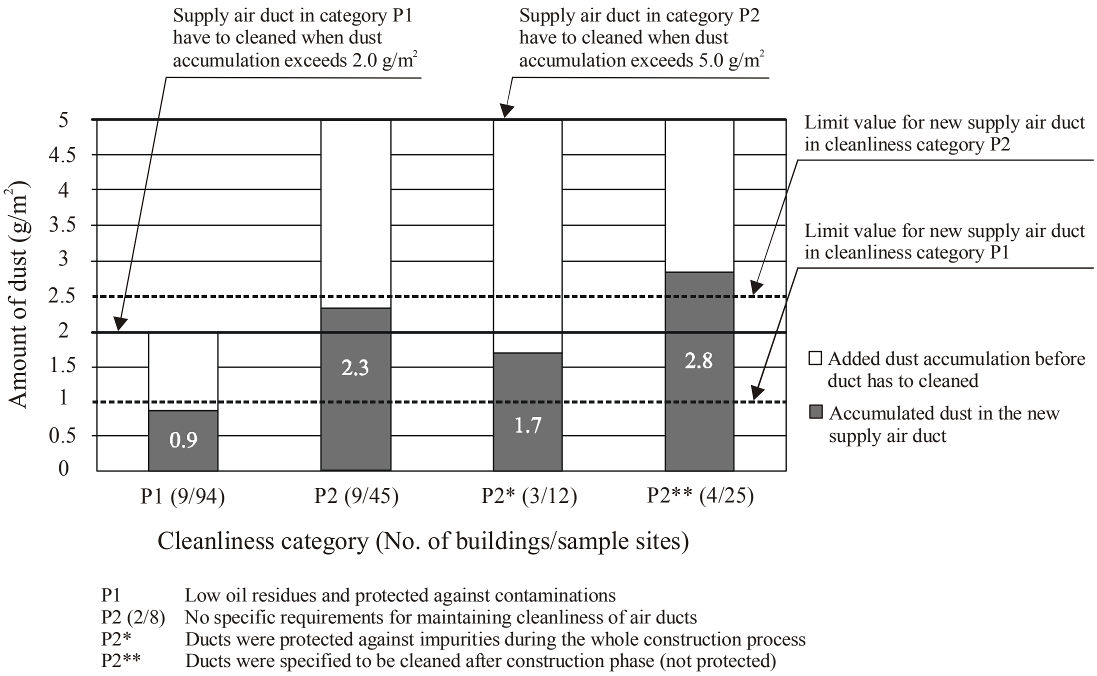


Figure 6.2. Amount of accumulated dust in categories P1 and P2 ducts and present limits values (FiSIAQ, 2001).

6.3 Efficiency of duct cleaning methods

6.3.1 Performance with ASHRAE test dust

The mean amount of dust on the surface of the ducts was 6.5 g/m^2 (4.8–8.7 g/m^2) before mechanical brushing ($MB1-MB2$) and 0.4 g/m^2 (0.2–0.8 g/m^2) after brushing (III). Before compressed air cleaning ($CAC1$), the mean amount of dust was 6.5 g/m^2 (5.3–7.2 g/m^2) and 0.6 g/m^2 (0.1–1.0 g/m^2) after cleaning. In category P1 ducts, the mean amount of residual dust was significantly lower ($P < 0.0001$) after mechanical brushing than after compressed air cleaning. In category P2 ducts, the mean amount of residual dust was slightly higher after mechanical brushing ($MB1$) than after compressed air cleaning. However, the mean amount of residual dust was lower ($P < 0.2$) after mechanical brushing ($MB2$) (brush was covered with a polyester cloth) than after compressed air cleaning. In the plastic ducts, the mean amount of residual dust was significantly higher ($P < 0.02$) after mechanical brushing ($MB1$) but it was not significantly higher ($P < 0.08$) after mechanical brushing ($MB2$) than after compressed air cleaning.

According to visual inspection, the inner surface after the inner 90° bend had more dust residues (at a distance of 0.5 m) than the surfaces elsewhere in the ducts after cleaning. This was a result of the fact that the flexible shaft pushed the brush and the air nozzle to the outer surface of the duct after the 90° bend.

6.3.2 Laboratory test with dust accumulated at construction site

The mean amount of dust was 4.3 g/m^2 (1.0–10.1 g/m^2) before mechanical brushing ($MB3-MB6$) and <0.1 g/m^2 (<0.1–0.1 g/m^2) after brushing (III). The category P2 ducts were visually clean after mechanical brushing. Only some water stains or oil residues were observed after brushing. The mean amount of dust was 3.5 g/m^2 before compressed air cleaning ($CAC2$) and <0.1 g/m^2 after cleaning. Upon visual inspection, there was only a small amount of residual dust on the inner surface of the category P1 ducts after compressed air cleaning.

The mean amount of residual dust was below the detection limit of the vacuum test method (0.1 g/m^2). The detection limit was defined as the standard deviations of the blank samples used for the quality control multiplied by six (Jaarinen and Niiranen, 2000).

6.3.3 Field measurements

The mean amount of dust was 0.8 g/m^2 (0.6–0.9 g/m^2) before mechanical brushing ($MB7-MB10$) and 0.2 g/m^2 (0.1–0.2 g/m^2) after brushing (III). Before compressed air cleaning ($CAC3$), the mean amount of dust was 5.4 g/m^2 (samples included a lot of steel dust) and 0.3 g/m^2 after cleaning. The mean amount of residual dust was lower after mechanical brushing than after compressed air cleaning. However, the difference was not significant ($P < 0.08$). The measured speed of the airflow in the ducts was, on average, 10 m/s (5–17 m/s) before mechanical brushing.

Table 6.1 presents the amount of dust before and after cleaning and the measured speed of airflow in the cleanliness category P1 ducts of the laboratory test with ASHRAE test dust and the field tests.

Table 6.1. Amount of dust and measured speed of airflow in category P1 ducts before and after duct cleaning in laboratory tests with ASHRAE test dust and field tests.

Cleaning method	Laboratory test with ASHRAE test dust		Speed of airflow	Field test		Speed of airflow
	Before (g/m^2)	After (g/m^2)	v (m/s)	Before (g/m^2)	After (g/m^2)	v (m/s)
Mechanical brushing [a]	6.5	0.2	10	0.8	0.2	10
Compressed air cleaning [b]	7.2	1.0*	24	5.4	0.3	– [c]

[a] Number of samples was 5 in the laboratory test and 28 in the field test
[b] Number of samples was 5 in the laboratory test and 4 in the field test
[c] Dust was blown out of the ducts (length of 20 m) into the surrounding space by the air dusting gun without a vacuum collector
* *T*-test: Comparing means of residual dust in the ducts after mechanical brushing and compressed air cleaning, $P<0.0001$

6.4 Model of duct cleaning brush

6.4.1 Rotating bristle simulations

In the simulations, which were carried out to show rotating bristle behaviour in a duct, the bristle cross-section was taken to be circular with length $L = 0.175\,\text{m}$, thickness $d = 1\times10^{-3}\,\text{m}$, cross-sectional moment of inertia $I = \pi d^4/64 = 4.909\times10^{-14}\,\text{m}^4$, density $\rho_\text{b} = 1140\,\text{kg/m}^3$, friction coefficient $\mu = \pi_3 = 0.5$ (in IV and VI the friction coefficient was 0.7), density of air $\rho_\text{a} = 1.2\,\text{kg/m}^3$, kinematic viscosity of air $\nu_\text{a} = 1.528\times10^{-5}\,\text{m}^2/\text{s}$, bristle length duct radius ratio $\zeta = \pi_2 = L/R = 1.1$ ($R = 0.1575\,\text{m}$) and Young's modulus $E = 2.8\,\text{GPa}$, corresponding roughly to the data for nylon (Viljamaa and Eriksson, 2003) (IV and VI). The friction coefficient value was estimated from the results of the laboratory test (Rautiainen, 2002). The effect of air drag was studied by using the reduced air speed coefficient value $c = 0$ (no air drag) and $c = 1$ ("full" air drag). The simulations were performed for a brush where the number of bristles was $n = 1000$.

Figure 6.3 shows the deflection of bristles with the rotation speeds $n = 0\,\text{rpm}$, $n = 500\,\text{rpm}$, $n = 1000\,\text{rpm}$ and $n = 2000\,\text{rpm}$.

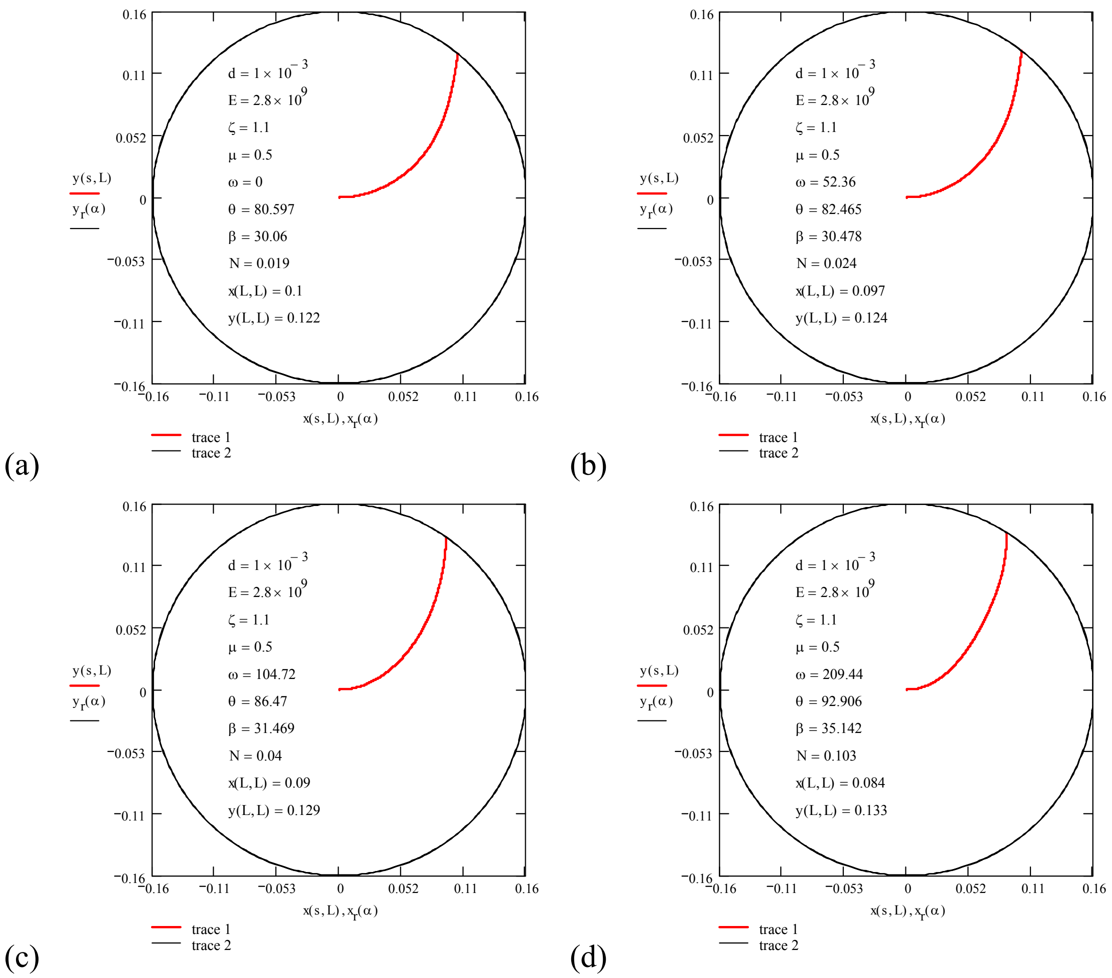


Figure 6.3. Deflected form of the bristle (a) bristle rotation speed n=0 rpm, (b) n=500 rpm, (c) n=1000 rpm and (d) n=2000 rpm. The units of the quantities in the figures are [d]=m, [E]=Pa, [ζ]=–, [μ]=–, [ω]=rad/s, [θ]=°, [β]=°, [N]=N, [x]=m, [y]=m.

The deflected shape of the bristle changes with the rotation speed of the bristle (IV–VI). At the rotation speed $n = 0$ rpm (impending motion is assumed, so friction is included) the bristle is deformed rather symmetrically with respect to its ends. As the rotation speed of the bristle increases, the deformation of the bristle seems to concentrate nearer the rotation centre.

6.4.2 Effect of design parameters on performance of cleaning brush

The normal force and the contact angle increase roughly quadratically in the interval for practical purposes ($n = 0 - 3000$ rpm) (IV). For the unrealistic high rotation speed (over 6000 rpm), the accuracy of the discrete solution may be questionable but, in any case, the shape obtained with "a hook" at the contact end intuitively seems correct, given the very large centrifugal forces trying to straighten the bristle.

The increase of the duct radius and, correspondingly, the length of the bristle affect the bristle shape in a way similar to the increase of the rotation speed. Additionally, the deformation of the bristle concentrates more at both ends of the bristle when the duct radius increases sufficiently.

As the centrifugal forces are proportional (through A) to the second power of d and the elastic forces (through I) to the fourth power of d, it is to be expected that, with higher values of d, the shape of the bristle approaches that corresponding to $n = 0\,\text{rpm}$. The normal force is seen to grow rapidly as a function of d. The contact angle decreases somewhat with d, which is also advantageous for cleaning efficiency.

The increase of the Young's modulus naturally increases the bristle stiffness. However, the change in the Young's modulus has only a slight effect on the bristle deflection in the range of 2.0–3.5 GPa. The normal force increases a little and the contact angle decreases very slightly when the value of the Young's modulus is varied around the theoretical value of nylon, app. 2.4 GPa (Allmeasures, 2003).

Table 6.2 summarizes the dependence of the normal force and the contact angle on various parameters. The percentage changes are referred to the values obtained by the lower values of the four parameters. The parameters values were used in general for the rest of the quantities, except for the parameters in question, which were varied to see their effect on the results.

Table 6.2. Dependence of normal force and contact angle on various parameters.

Parameter (range)	Normal force N Influence	Normal force N Difference (%)	Contact angle β Influence	Contact angle β Difference (%)
Rotation speed (n=0–2000 rpm)	+ + + +	442	+ +	17
Radius of duct (R=0.1–0.4 m)	– –	–25	+ + +	52
Thickness of bristle (d=5×10^{-4}–2×10^{-3} m)	+ + + +	12600	–	–4
Young's modulus (E=2×10^{9}–3.5×10^{9} Pa)	+ + +	53	–	–1

–/+=slight negative/positive dependence (difference ≤5%)
– –/+ +=negative/positive dependence (5%< difference ≤50%)
– – –/+ + +=strong negative/positive dependence (50%< difference ≤100%)
– – – –/+ + + +=very strong negative/positive dependence (difference >100%)

6.4.3 Effect of dimensionless design parameters of cleaning brush

The dimensionless normal force increases roughly linearly when $\pi_1 = \rho_{\mathrm{b}} A \omega^2 L^4 / EI$ ranges of the value are used in practical purposes (IV). As is to be expected, the magnitude of the normal force and the contact angle increase when parameter $\pi_2 = L/R$ grows. Both the magnitude of the normal force and the contact angle increase roughly quadratically as a function of π_2. With higher values of π_2, the bristle "has to bend more to fit in the duct" so the results intuitively seem to be correct. The growth of the dimensionless number $\pi_3 = \mu$ acts in an opposite manner to π_1 and π_2 to the magnitude of the normal force and the contact angle. The decrease of the normal force with increasing π_3 seems plausible as the friction force has a direction with "large bending influence". To achieve high normal contact force, π_3 should be low.

Table 6.3 summarizes the dependence of the dimensionless normal force and the contact angle on various design parameters of the cleaning brush. The percentage changes refer to the values obtained by the lower values of the three parameters. The parameters values were used in general for the rest of the quantities, except for the parameters in question, which were varied to see their effect on the results. The value of $\pi_1 = 500$ corresponds approximately to the rotation speed of 2850 rpm (with Young's modulus value $E = 2\,\text{GPa}$). The percentage changes refer to the values obtained by the lower values of the three parameters.

Table 6.3. Dependence of dimensionless normal force and contact angle on various parameters.

Dimensionless number (range)	Dimensionless normal force $\overline{N}$ Influence	Difference (%)	Contact angle β Influence	Difference (%)
Effect on centrifugal force ($\pi_1 = \rho_b A \omega^2 L^4 / EI$=0–500)	+ + + +	916	+ +	40
Length radius ratio ($\pi_2 = \zeta = L/R$=1.05–1.3)	+ +	45	+ + + +	145
Friction coefficient ($\pi_3 = \mu$=0.1–0.9)	– – –	–67	– –	–21

–/+=slight negative/positive dependence (difference ≤5%)
– –/+ +=negative/positive dependence (5%< difference ≤50%)
– – –/+ + +=strong negative/positive dependence (50%< difference ≤100%)
– – – –/+ + + +=very strong negative/positive dependence (difference >100%)

6.4.4 Effect of air drag on rotating bristle behaviour

The deflection of a bristle in the duct does not change significantly due to air drag at practical rotation speeds (VI). Air drag somewhat decreases both the magnitude of the normal force N and the contact angle β. However, the effect of air drag is significant to some extent for the torque T^* from one bristle (superscript symbol ∗ is used here for the torque from one bristle to differentiate it from torque from a brush). The ratio $T^*_{\text{ad}} / \left(T^*_{\mu} + T^*_{\text{ad}}\right)$ at the rotation speed of 2000 rpm is 10% and 37% with the reduced air speed coefficient values $c = 0.5$ and $c = 1$, respectively.

6.4.5 Dependence of simulation result on degree of approximation

Table 6.4 presents some results from the simulations with the degree of approximation $n = 4$, $n = 6$, $n = 8$ with Young's modulus value $E = 2\,\text{GPa}$ at the rotation speed of 1000 rpm (V).

Table 6.4. The value of the undetermined parameters, the normal force, the contact angle and the inclination angle at a rotation speed of *n*=1000 rpm.

Parameter (unit)		Degree of approximation *n*		
		n=4	*n* =6	*n*=8
c_1	(1/m)	33.3183	29.3911	32.4252
c_2	(1/m^2)	-412.903	-391.401	-566.407
c_3	(1/m^3)	2760.41	3490.11	8286.09
c_4	(1/m^4)	-6652.60	-16735.7	-89367.3
c_5	(1/m^5)		47417.9	682115
c_6	(1/m^6)		-77832.7	-3246440
c_7	(1/m^7)			8366080
c_8	(1/m^8)			-9038080
N	(N)	0.0374726	0.0374739	0.0369180
β	(°)	34.1461	35.1692	35.3745
θ	(°)	101.711	98.1211	99.1485

The results obtained in the example cases show that the values obtained with $n = 4$, $n = 6$, $n = 8$ do not differ greatly. Additionally, the degree of the approximation $n = 6$ and $n = 8$ gave roughly the same results in the preliminary simulation of a known analytical solution of the Elastica problem (Timoshenko and Gere, 1961).

6.4.6 Verification of the results

To verify the results of the simulation, the laboratory measurements with the rotation speeds of 0 rpm, 500 rpm and 1000 rpm were carried out. The deflection of the bristle pair and the brush in the duct is shown in Figure 6.4 (IV and VI).

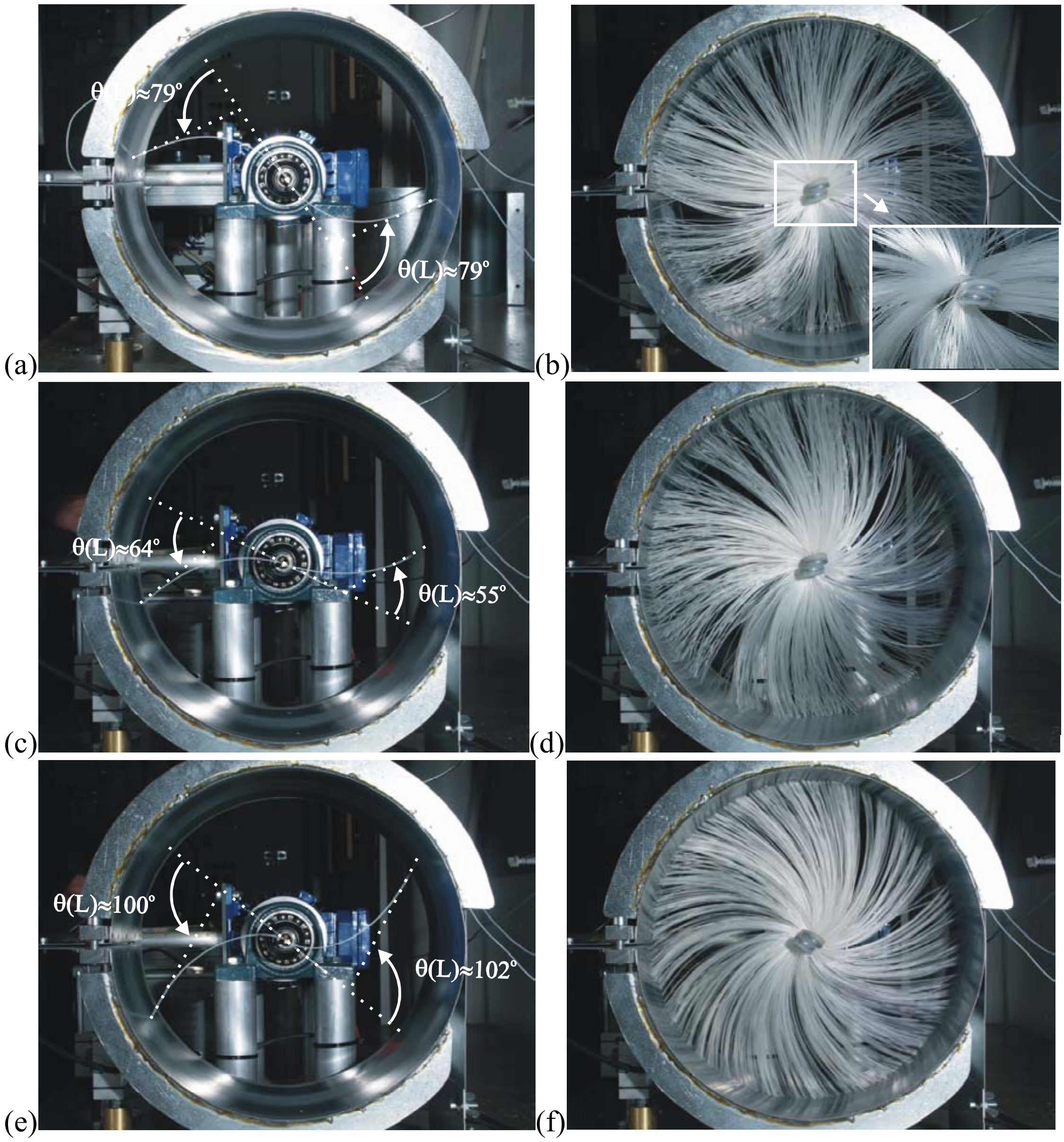


Figure 6.4. Deflected form of the bristle (a) bristle rotation speed n=0 rpm, (c) n=500 rpm and (e) n=1000 rpm in the duct with contact. Deflected form of the brush (b) brush rotation speed n=0 rpm, (d) n=500 rpm and (f) n=1000 rpm in the duct with contact.

The deflection of the bristle pair is quite similar to that obtained by the simulation with $n = 0\,\text{rpm}$ and $n = 1000\,\text{rpm}$ (Figure 6.3 (a) and (c)). At a rotation speed of $n = 500\,\text{rpm}$, the bristle pair was found not to remain in the plane assumed in the simulation and therefore the deflection of the bristle pair seen in the photograph is small compared to that obtained by the simulation. The deflections of bristles of the brush are difficult to estimate accurately because the bristles were connected asymmetrically on a spiral frame made of metal wire (Figure 6.4 (b)).

Figures 6.5 (a) and (b) present the magnitude of torque T due to air drag evaluated from measuring results (equation (5.50)) when the brush is rotated in air as functions of the rotation speed. Additionally, the torque from the simulation T_s using the values of a reduced air speed coefficient (equation (5.14)) $c = 0.5$ and $c = 1$ is calculated from

$$T_s = n\int_0^L q(s')r(s')\cos\gamma(s')\,\mathrm{d}s', \tag{6.4}$$

where n is the number of the bristles.

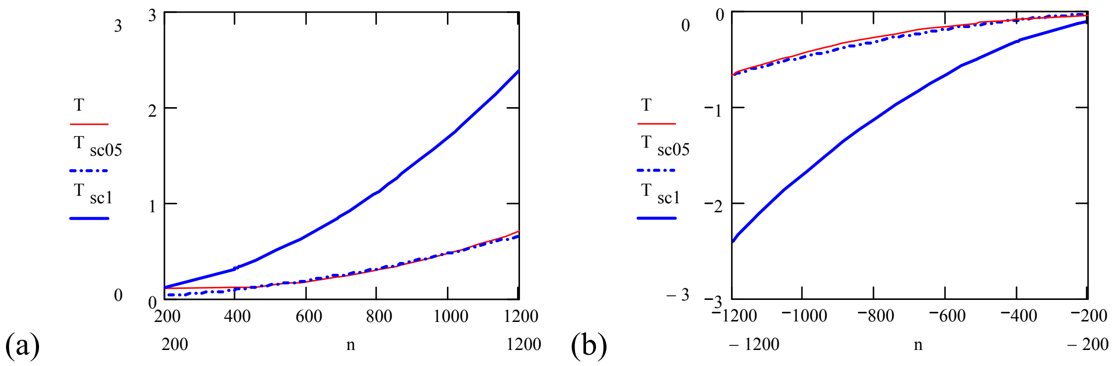


Figure 6.5. The measured T [Nm] and simulated torque T_s [Nm] due to air drag with $c = 0.5$ and $c = 1$ when the brush rotates in air as functions of the rotation speed n [rpm].

The results of the laboratory test and the simulation are nearly identical with $c = 0.5$ in the simulation. With $c = 1$, the simulation gave values that were too large, which was to be expected due to the bulk air motion found to be present in the experiments.

7 DISCUSSION

7.1 Dust measuring methods

The results showed that the vacuum test method had the greatest efficiency in collecting dust from the duct surface (I). Similar results have also been obtained in a study conducted in old supply air ducts (Fransson et al., 1995). In this study, a 100% collection efficiency was not defined in the field due to the lack of a complete reference method. In another study, the relative collection efficiency (RCE) of the vacuum test method was 0.02–0.9, depending on the sampling technique of the method (Fitzner et al., 2000). Upon on visual inspection, residual oil on the round duct surface decreased the dust sampling efficiency of the vacuum test method (III). Additionally, dust was found to deposit onto the surface of the suction hose and the wall of the filter cassette (I–III). The most reliable results can be achieved by weighing the filter cassette with the filter and the hose together (Pasanen, 1999). In this study (I), 22% of the dust sample adhered to the inner surface of the straight suction hose. Therefore, the suction hose should be short and straight to minimize the wall loss. When the dust accumulation was determined by weighing the whole sampling set, the detection limit of the vacuum test method was approximately 0.1 g/m^2. A similar result has been reported in (Asikainen and Pasanen, 2002).

The surface dust level measured with the gravimetric tape method was only slightly lower than that measured with the vacuum test method. The results indicate that the tapes used in the study are effective and reliable for dust sampling when the dust layer is thin. Similar findings have been reported in a previous laboratory study where an upper limit of 4 g/m^2 was suggested for the gravimetric tape method (Pasanen, 1999). The dynamic range of the tape method might possibly be extended upwards by taking an additional dust sample. The edge effects could be omitted by using a tape with a slightly smaller surface area. In new supply air ducts, the amount of dust is normally low enough for the tape to collect most of the dust from the surface (I–II).

The optical method was found to be the easiest to use in the field measurements. Unlike the gravimetric tape method, no correlation between the optical method and the vacuum test method was found. The relation between the optical and gravimetric methods depends on particle density and size distribution. Additionally, the projected area, as measured with the optical method, is approximately independent of the optical properties of the particles (Schneider et al., 1996). The fitting function (6.1) gives approximately the same values (difference ±8%) as the function (6.2) of Fransson et al. (1995) when the amount of dust accumulation is in the range of 1.0–1.6 g/m^2 measured with the gravimetric tape method. However, the fitting function (6.1) gives higher cleanliness values than recommended in the Norwegian guidelines (Juell et al., 1994) for the limit values of the accumulated dust (<3% and <5%) in new air ducts.

7.2 Effect of cleanliness control on dust accumulation

The results of the field study showed that the limit value of 1.0 g/m^2 for accumulated dust, when set as the criterion for cleanliness category P1 (FiSIAQ, 2001), is possible to achieve if the ducts are carefully protected against dust in all phases from manufacturing to installation (II). The average amount of accumulated dust in the systems with minor protection (cleanliness category P2 ducts) was about half of that found in the supply air ducts of recently built buildings (5.1 g/m^2) (Pasanen, 1998). The efficiency of the protection of duct endings with caps was shown as a low amount of dust in the P2 category ducts. Thus, dust accumulation in the duct can be partly avoided by duct protection during the whole construction phase. Benefits are achieved especially during phases when the particle concentration is very high in the air at the building construction site (Luoma, 2000).

At present, the abrasive cutting machine is commonly used for duct installation work. However, the use of non-abrasive methods for cutting the ducts is recommended (Luoma and Kolari, 2002), although the steel filings on the supply air duct surface might have only a slight effect on the quality of the supply air. According to visual evaluation, some of the samples that were taken close to the access openings in the middle of the ductworks contained large amounts of steel filings because the ducts had been cut with an abrasive cutting machine. The density of steel is much higher than that of dust, and it increased the mass of the samples considerably. The cutting technique used for round air ducts may be one of the reasons why the dust accumulation was higher in round air ducts compared to rectangular ducts.

7.3 Efficiency of duct cleaning methods

In the laboratory test with ASHRAE test dust, the best cleaning result was achieved by mechanical brushing in category P1 and P2 metal ducts (III). In the plastic ducts, the least mean amount of residual dust was measured after compressed air cleaning, but compared to the brushing methods it was somewhat slower. In a previous laboratory study with ASHRAE test dust, the mean amount of dust was 4.2 g/m^2 (0.7–11.1 g/m^2) before mechanical brushing and 0.1 g/m^2 (<0.1–0.4 g/m^2) after brushing (Jalonen, 2000). In this study, neither mechanical brushing nor compressed air cleaning was effective enough to remove residual oil sufficiently from the category P2 ducts surfaces. The negative effect of oil residues on the effectiveness of cleaning was noticed only upon visual inspection because the vacuum test method was not capable of collecting all the dust from the oily surface.

In the other laboratory test with dust accumulated at the construction site, the amount of residual dust was mostly below the detection limit of the vacuum test method. Therefore, the respective cleaning efficiencies of the mechanical brushing and compressed air cleaning methods were evaluated by comparing the amount of residual dust in the laboratory test with ASHRAE dust and the field test only.

The difference between the cleaning results in the laboratory tests with two types of dust might depend on several factors. One reason may be the different duct cleaning arrangements: the whole ductwork with two pieces of 90° bends was cleaned once back and forth in the test with ASHRAE dust, whereas only the straight parts of duct were cleaned in the other laboratory test. The bends of the ductwork made the duct cleaning more difficult and especially affected the cleaning efficiency immediately (at the distance 0.5 m) after the bends. The other reasons may relate to the different quality of the dust used in the laboratory tests as well as to the different amount of oil residues, especially in category P2 ducts before cleaning. Additionally, the speed of airflow was lower in the laboratory test with ASHRAE dust than in the other laboratory test before mechanical brushing.

In the field test, the ducts were normally brushed at least twice in order to achieve an acceptable cleaning result visually. The mean amount of residual dust was low despite the varied initial level of the dust accumulation before cleaning. In a previous study of new supply air ducts, the mean amount of dust was 1.8 g/m^2 (0.2−10.8 g/m^2) before mechanical brushing and 0.2 g/m^2 (<0.1−0.7 g/m^2) after brushing (Jalonen, 2000). In a more recent study of old air ducts, the mean amount of dust was 8.4 g/m^2 (0.7−47.0 g/m^2) before mechanical brushing and 1.9 g/m^2 (<0.1−8.8 g/m^2) after brushing (Kolari, 2003). Similar results have been reported in (Kulp et al., 1997; Holopainen et al., 1999; Puhakka et al., 2003). Additionally, the cleaning work of the old supply ducts was performed from one to three times before the acceptable cleaning result (≤1.0 g/m^2) (FiSIAQ, 2001) was achieved (Puhakka et al., 2003). The results indicate that newly deposited dust (i.e. dust deposited within months) is easier to dislodge from the duct surface than dust that has been deposited for a longer time (i.e. for a number of years) in the duct. The measured speed of airflow in the ducts before mechanical brushing was, on average, 10 m/s, which is lower than recommended for industrial ventilation, i.e. 13 m/s and over depending on the nature of contaminant (ACGIH, 1988). On the other hand, the cleanliness level after duct cleaning was acceptable, despite the low speed of the airflow in the ducts. According to visual inspection and the measured value, the best results were achieved with mechanical brushing. Compressed air cleaning with an air dusting gun was suitable for cleaning a small area of ductwork.

7.4 Model of duct cleaning brush

The model provides insight into the behaviour of the bristle of a rotating duct cleaning brush. In general, the experimental results obtained allow some confidence in the validity of the proposed simulation model to enable it to be used in analysing and comparing different brush designs. As expected, the model overestimates the effect of the air drag of a brush with $c = 1$ (IV and VI). These results are thus "on the safe side" with respect to the power need. A value $c = 0.5$ was found to give a good agreement with experimental results in one test case (VI). However, this value will not necessarily work well with other brush types. The torque increases roughly quadratically at the rotation speed of 300−1000 rpm due to air drag. Because of the air drag, both the magnitude of the normal force and the contact angle decrease when the rotating speed of the bristle increases.

Dimensionless numbers $\pi_1 = \rho_b A\omega^2 L^4 / EI$ and $\pi_2 = L/R$ are the parameters that can be used to optimise the duct cleaning brush (IV). In rotating brush duct cleaning, the common range of π_1 and π_2 are $0 < \pi_1 < 100$ and $1 < \pi_2 < 1.3$, respectively. The manufactures of the brushes can affect $\pi_3 = \mu$ by selecting a suitable material property for the bristle. The deflection of the bristle in the duct does not change significantly due to air drag at practical rotation speeds, so dependencies on the dimensionless numbers π_4 and π_5 are not considered.

The results obtained in the studied cases showed that values obtained with the degrees of approximation $n = 4$, $n = 6$, $n = 8$ do not differ greatly (V). Additionally, the approximation with $n = 6$ and $n = 8$ gave roughly the same results in the preliminary simulation of a known analytical solution. Thus, from the design point of view, case $n = 6$ was judged to already be quite acceptable in terms of being able to be employed in practice.

The approximation using only four Lagrangian interpolation functions for integration purposes in IV and VI may be considered rather crude. Higher order Lagrangian interpolation functions could be used. However, it is well known that these start to behave badly at the ends of the interval; it appears, therefore, to be unwise to go higher than $n = 4$ (Irons and Ahmad, 1980). Roughly the same results were obtained in V using the formulation based on Simpson's integration rule. Although the Lagrangian interpolation approach is simpler to program, it has a drawback in that it cannot be extended to obtain the high degree of accuracy needed when a large number of undetermined parameters is used. The application of Simpson's rule does not have this drawback. It is also obvious that one cannot go "very far" in using monomials as the basis function as they start to resemble each other "too much". For instance, in this case, sine functions could be an alternative in obtaining suitable basis functions.

It is obvious that, without a centralizing device, the rotation centre of the brush cannot situate exactly at the centre of the duct (IV). Some eccentricity is needed for the contact forces of the brush to produce an upwards-directed resultant to give equilibrium with gravity. If the rotation centre of the brush remains roughly stationary, each brush obtains a periodic motion in the rotating coordinate system. It should be further mentioned that taking the gravity of an individual bristle into account, even in the case of no eccentricity, leads in fact to a periodic response, as the direction of the gravity in the rotating coordinate system depends on the orientation of the coordinate system.

It was assumed that a large contact normal force N and a small contact angle β are advantageous for cleaning efficiency. Therefore, the thickness of the bristle can be considered as the most efficient parameter studied. As was mentioned previously, theoretical and experimental work is needed to clarify the roles of N and β in the cleaning process (IV). Additionally, this work is limited to the evaluation of the bristle behaviour in round ducts. A bristle model for rectangular ducts leads to a highly complex time-dependent problem. However, extensions of the modelling procedures presented above could probably make this problem solvable as well.

7.5 Recommendations on verification of cleanliness, installation and cleaning of new air handling system

Although visual inspection is a subjective method, it can successfully be used to estimate the need for cleaning and to verify the results of the cleaning work of air handling systems in parallel with other objective measuring methods. A trained and experienced inspector can estimate visually quite accurately the amount of dust accumulation in relatively clean (1–2 g/m^2) new air ducts (Holopainen et al., 2002). The visual inspection method is based on a systematic inspection of air ducts that compares the amounts of dust and debris found in the ducts to those marked on a visual cleanliness scale and then records the results on an inspection form. Dust measuring methods that are more objective are needed if an experienced inspector cannot make a clear decision as to the necessity to clean ducts or whether the duct cleaning work should be verified. Additionally, the results of the evaluation should be documented for the next periodic inspection.

The results of the study indicate that protection against dust during the construction process and using ducts with low oil residues are the practical ways to achieve high cleanliness levels of air handling system installations. Oil residues are difficult to clean properly and therefore new installations should consist of oil-free ducts and components. The use of non-abrasive cutting methods is recommended for the installation work of air handling systems. The results also indicate the importance of training instruction workers, as well as the requirement that specific instructions and control regulations relating to the clean-installation methods must be adopted by all employees working on the construction. The Finnish guideline (FiSIAQ, 2001) gives useful instructions when aiming at the installation of a clean air handling system.

In order to obtain good cleaning results, the duct and its components have to be designed and installed with a sufficient number of access openings to allow the cleanliness of the ductwork to be inspected and maintained without difficulty (NADCA, 1995; CEN, 1997; HVCA, 1998; VDI, 1998; ME, 2003). If newly installed ducts have to be cleaned after construction, the cleaning should not be done until all construction work that produces dust to ambient air has been completed and the spaces of the building have been properly cleaned. The cleaning methods should be chosen according to the material of the duct surface and to the quality of accumulated dust. Additionally, the vacuum collection device with appropriate air filters should be used to capture and convey dust dislodged during the cleaning process. Ducts should be cleaned the number of times necessary for an acceptable cleaning result to be achieved visually. Verification of cleaning work has to be performed before the operation of the air handling system (NADCA, 1992; HVCA, 1998; NADCA, 2001).

8 CONCLUSIONS

Surface dust sampling methods are necessary for the quantitative evaluation of the need to clean air ducts and to control the quality of cleaning work. The vacuum test method showed the greatest ability to collect dust from the duct surface and is suitable as a reference method for the objective determination of surface dust levels. The gravimetric tape method can be applied particularly to duct surfaces with low amounts of recently deposited dust and is quick to use in the field. The optical method is also convenient for field application but its accuracy is lower than that of the gravimetrical methods. All the methods studied can be applied to the verification of the cleanliness of new air ducts when the surface dust level is relatively low (0.1−1.0 g/m^2).

The results of the field test showed that dust accumulation in ducts, which were protected against contaminations and had low oil residues, was significantly lower than in ducts that had only minor requirements for maintaining the cleanliness. The highest mean amount of dust was accumulated in the middle of the ducts and near the terminal units. In the round ducts especially, steel filings were found close to the openings where ducts had been cut with an abrasive cutting machine. Non-abrasive cutting methods are therefore recommended for use in the installation work of air handling systems.

Several cleaning methods can be used to remove dust from the surfaces of the ducts. The methods should be chosen according to the material of the duct surface. Mechanical brushing is an efficient cleaning method to achieve a good cleanliness level for practical purposes (≤0.2 g/m^2) in newly installed cleanliness category P1 ducts. The compressed air cleaning is also efficient method especially in newly installed plastic ducts. The oil residues on the inner duct surface make duct cleaning difficult, while the dry cleaning methods studied are not efficient enough to remove sticky contaminants. Therefore, new installations should consist of oil-free ducts and components.

According to the simulation, the bristle thickness was the most important parameter studied in connection with assumed duct-cleaning effectiveness. Additionally, the normal force can be increased significantly by using a higher bristle rotation speed. With normal brush properties, air drag increases the torque needed and decreases somewhat the contact force between a bristle tip and the duct surface. However, air drag only slightly affects the deflections of the bristles within the practical rotating speed range of the brush (300−1000 rpm) in a round duct. The results of the simulation showed that the values obtained with the degrees of approximation $n = 4$, $n = 6$, $n = 8$ do not differ greatly. The numerical integration methods − Simpson's integration rule and application of Lagrangian interpolation − gave approximately the same results with the degree of approximation $n = 6$. In conclusion, the developed simulation model seems to be a useful tool in cleaning-brush design work.

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ORIGINAL PUBLICATIONS

I The field comparison of three measuring techniques for evaluation of the surface dust level in ventilation ducts

II The effect of cleanliness control during installation work on the amount of accumulated dust in ducts of new HVAC installations

III Effectiveness of duct cleaning methods on newly installed duct surfaces

IV Modelling bristle behaviour in rotating brush duct cleaning

V Large deformation analysis of a rotating bristle in brush duct cleaning

VI Rotating brush behaviour in duct cleaning