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ORIGINAL ARTICLE

Design and simulation of dust extraction for composite drilling

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Abstract Due to its high strength-to-weight ratio, composite materials have been widely applied in aerospace manufacturing. However, some challenges are facing in fabrication and assembly of the parts with composite materials. One of them is how to collect the dwarf and dust generated from the drilling operation, especially in an open environment when the composite parts are assembled, since a large number of holes need generating to rivet the parts together when the parts with composite materials are assembled in an aircraft structure. The efficiency of dust extraction is crucial to the healthy operating environment and the quality of the assembled component. In this paper, three conceptual designs of automatic dust extraction are proposed and compared, and the best design with the hood fastened on the drilling spindle has been selected and analyzed. Its design parameters have been identified; a systematic procedure has been proposed for the design optimization; the process of the dust extraction has been modeled and simulated using the COSMOSFloWorks. Taguchi method is applied to optimize the design. The process of the dust extraction has been validated through animation.

Keywords Composite drilling · Dust extraction · Modeling and simulation · Taguchi method · Simulation-based optimization · COSMOSFloWorks

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1 Introduction

Composites offer increased strength, reduced weight, and a resistance to the two factors that can compromise metallic structure—fatigue and corrosion [12]. Composites materials become favorite choice for many commercial airplane applications. As an example, Airbus aggressively replaced traditional aluminum and titanium materials with composites to achieve significant weight savings and lead to better fuel economy and a lower operating cost [23]. A comprehensive introduction on the evolution of composites manufacturing technology and its applications in aerospace industry has been given by [24]. In applying composite material in an aircraft structure, automation for both of the drilling process and the dust collection is desirable to improve the productivity and achieve consistent quality of products.

1.1 Automation of drilling process

When the parts of composite materials are assembled into a structure, two widely used types of joints are mechanical and adhesive bonds. Adhesive joints enable the distribution of the load over a larger area than do mechanical joints, but the disadvantage is that adhesives require careful surface treatments, and joints are difficult to disassemble for inspection and repair. Therefore, mechanical joints are preferable in most aerospace applications. A large number of the holes have to be generated. Take an example of the products from Airbus, the average number of holes of each wing is around 14,000, and of the Airbus company widely, 50 millions of holes have to be generated. The drilling process takes 70% of the wing-box assembly [17,25]. It is worth to note that the drilling during the assembly cannot be performed on the traditional machine tool, whose workspace is encapsulated. It becomes very challenging to collect the dusts in an open workspace.

Aerospace manufacturers will benefit from high throughout and consistent quality from drilling automation. A few of the products have been developed to automate the drilling operations at the phase of aircraft assembly. For examples, Atkinson et al. [2] used the Kuka robots for drilling automation where 80% of the holes on the component [2] can be drilled by robots. Devlieg and Feikert [8] developed a robot system capable of drilling, inspecting, and fastening. Thompson et al. [21] introduced a multi-spindle flexible drilling system for circumferential splice drilling application of the 777 Airplane. However, the automation of the drilling processes has been focused and the collection of dwarf and dust has to be performed manually. At the Northern Ireland Technology Centre of the Queen's University Belfast, a new project called Parallel Kinematic Assisted Aerospace Assembly is ongoing [4,5]. One of its main objectives is to provide a complete automation solution for both of drilling and dust extraction. The presented paper is a portion of the research outcome from this project.

1.2 The importance of dust extraction

Composite drilling can generate dusts. The fine dust particles generated remain suspended in the air for long periods, which are breathable to human being [3]. Inhaled particles from various occupational or environmental settings can act as irritants to the respiratory system [13]. There is growing evidence from the past decade that exposure to machining aerosols is associated with adverse respiratory health effects. Employees reported increased rates of skin irritation due to the foreign object debris [12]. Zhang et al. [27] studied the effects of composite material dust on the animals and confirmed that its impact on respiration systems of the animals.

Besides the safety concerns to the operators, if the dwarf and dust has not been collected appropriately, it would cause other problems such as the contamination of composite materials, the abrasive friction between two moving components, and the degradation of electrical components and wiring due to the contamination refers to the presence of a foreign material. Therefore, it is critical to develop a cost-effective solution for dust extraction in composite drilling.

1.3 Dust generation, extraction, modeling, and simulation

Because of the high amount and fineness of the dust produced and a potential risk of exposure to operators and aircraft components, all dust control measures are necessary to collect dust. The most effective way is to collect the dust at the source. To accomplish this, it is helpful to understand the conditions governing the production of dust during machining processes. Balout et al. [3] studied how the machining parameters influence dust generation during dry machining. Khettabi et al. [15] conducted the similar studies and concluded that the quantity and particle size of machining dust depend on cutting parameters, tool material, work piece material, and tool geometry, and the intensity of dust formation increases with an increase in cutting speed during turning and milling of almost all brittle materials. The dust formed when machining iron, steel, and brass at higher speeds has a much larger percentage of particles below 5 μm in size [11,26]. In addition to the cited factors, lubrication has a direct impact on the quantity and size of the produced particles [20].

Dust extraction is required widely in various applications from domestics, construction, and biotechnologies to manufacturing environment; numerous general-purpose dust extraction devices are commercially available. Taking an example, a comprehensive catalogue has been provided on various dust devices in construction [9]. Nevertheless, the applications of the commercialized products for the hole generation are confined due to the limited access to the operation area and the requirement of the high percentage of dust collection. A dust extraction device has to be tailored to the geometrics of a machining tool itself to achieve a better performance. Very few devices have been developed to collect the dust at the source of machining in an open manufacturing or assembly environment. The most relevant one is from the [14]. This company has patented an attachment with the milling spindle for dust extraction. However, its design and fabrication are very intriguing: The air ways of the dust extraction have been created in the body of the cutting tool, which can significantly increase the tool cost and reduce the stiffness and the life time of the tool. The designs in this paper are more generalized, and they avoid creating the airways in the body of the cutting tool.

Due to the complexity of fluid dynamics, the design of dust extraction is usually intuitive, which is mainly based on experience or experiments. For example, Thorne et al. [22] compared the performances of five dust extractions based on experiments. Nevertheless, the computational fluid dynamics (CFD) software tools have yet gained the acceptance for the design of dust extraction. Many CFD software tools, such as *Fluent* [1], *Comsol* [6], and *COSMOSFloWorks* [18], have been successfully applied in many areas such as combustion in an engine, weather prediction, animation, and virtual reality. Cook [7] discussed and classified them in terms of their features of pre-processing, modeling, solving, interface, post-processing, and user support. Kopyt and Gwarek [16] provided a comprehensive list of the available CFD software tools. The comparison of these software tools is out of the scope of this paper; the COSMOSFloWorks has been used in this study due to its availability.

1.4 The organization of the remained paper

For the automation of dust extraction in composite drilling, three design concepts have been conceived, and the comparison has made to select the best one for the dust extraction in an open workspace. The design parameters have been determined, and the COSMOSFloWorks is applied for the modeling and simulation of the extracting process. The Taguchi method and the analysis of variation (ANOVA) technique are used for the design optimization. The remained of the paper is organized as follows: In Section 2, three conceptual designs of dust extraction have been proposed, and their features are introduced and compared. In Section 3, the extracting process is modeled and simulated to establish the correlations between the design parameters and extracting performances. In Section 4, the Taguchi method and ANOVA technique are applied in determining the optimized set of design parameters. In Section 5, the main contributions have been summarized and the future research tasks are identified.

2 Conceptual designs

In composite drilling, the dwarf or dust is generated at the interface between workpiece and drilling tool. To capture the dusts at source, an extraction device can be attached either on the workpiece or on the drilling tool. In this section, three conceptual designs have been introduced.

2.1 Devices attached on workpiece

The optimization of the drilling processes for composite materials and stacks heavily relies on experiments [4,5]; a large number of experiments are required to optimize the drilling parameters, tool geometries, and drilling supports. A dedicated test platform is usually developed to conduct drilling experiments. The tests are usually performed on the standardized coupons. The instruments such as the dynamometer, high-speed camera, and scanning electron microscope are applied to monitor the drilling process and measure the drilling results. Since the geometrics of the tested coupons are given and they can be easily fixed on the machine tools, the devices of dust extraction can be attached on the coupons.

Figure 1 has illustrated two conceptual designs whose coupons/workpiece is attached with the dust extraction device. The design in Fig. 1a has two handles for dust extracting; they are fixed on the tested coupon. A dynamometer is installed under the coupon to collect the force signal in drilling process. The surrounding open space allows an operator or camera to observe the drilling process visually. A similar design in Fig. 1b has its extracting part mounted on the tested coupon as well; however, the hood is an encapsulated box which isolates the dust area from the environment. The transparent material such as organic glass is used to allow an observer to monitor the drilling process visually.

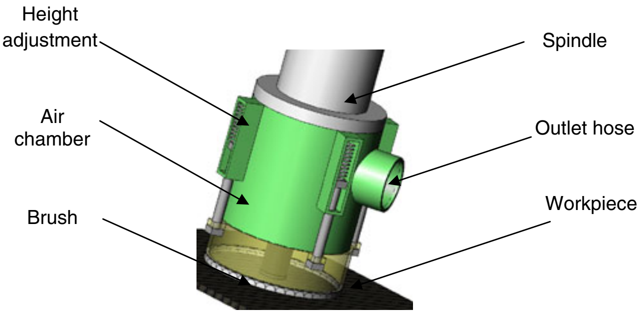
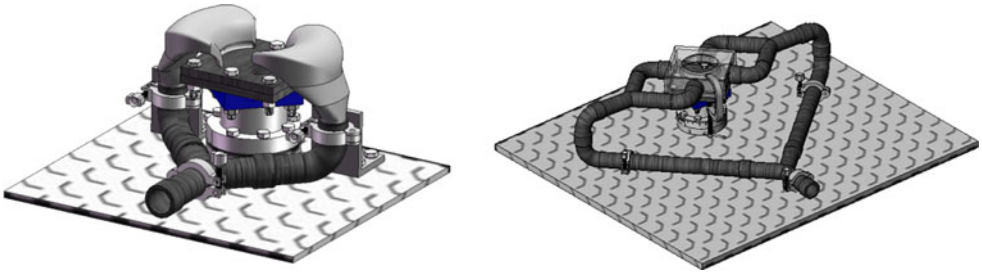


Fig. 2 Hoods attached on spindle

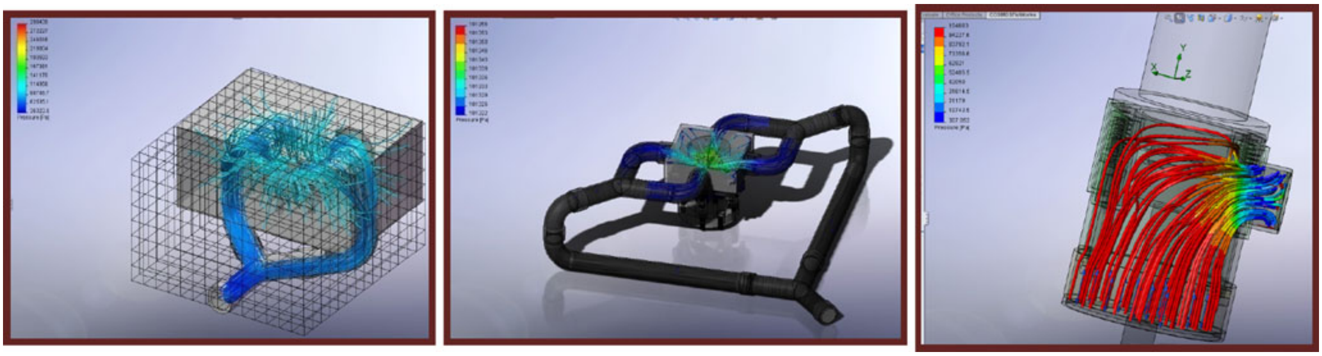
2.2 Device attached on machining spindle

Two designs in Section 2.1 are suitable to a dedicated test platform since the tested coupons have been specially designed. In actual drilling applications, however, it is impractical to mount the dust extraction on the workpiece. An alternative design has been shown in Fig. 2. Its dust

Fig. 1 Hoods attached on workpiece. **a** open hood, **b** closed hood



(a) open hood (b) closed hood



(a) open hood on workpice (b) closed hood on workpiece (c) closed hood on tool

Fig. 3 Comparison of three conceptual designs. **a** open hood on workpiece, **b** closed hood on workpiece, **c** closed hood on tool

extraction device is attached on the drilling spindle. It consists of a ring of brush, an adjustable cylinder, an air chamber, and the hose connected to the dust collector. A jig is designed to mount the air chamber on the drilling spindle. The adjustable cylinder is to compensate the change of the height from the upper surface of the workpiece to mounting surface of the dust extraction, since no auxiliary is required at the side of workpiece. This design is very suitable to be used together with industrial robots or parallel kinematic machines for the drilling operation at the phase of aircraft assembly.

2.3 Selection of conceptual design

The dust extraction attached on the spindle tool has been selected based to two main reasons: (1) it is more generalized and applicable to both of a lab environment and actual application using advanced robotic systems and (2) as shown in Fig. 3, the primarily simulations have illustrated that with the same specifications of the dust collector, the selected design is likely to achieve a better extracting performance. The details about the modeling and simulation as well as the evaluation criteria will be provided in the next section.

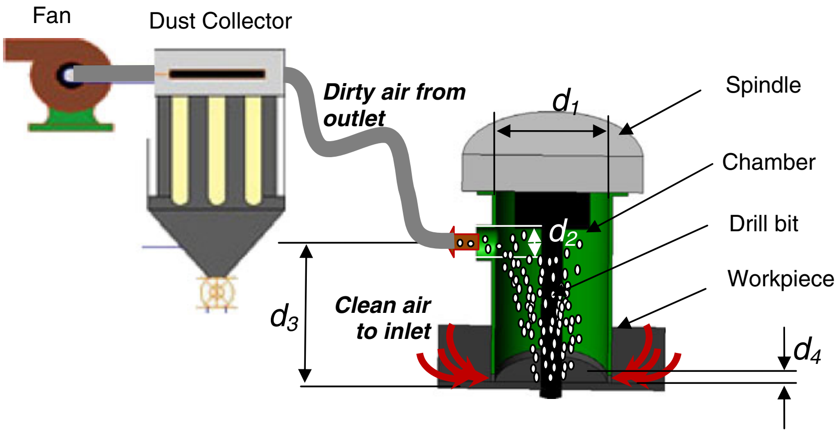
3 Modeling and simulation of dust extractions

The dust extraction attached on the spindle tool has been used as a case study for modeling and simulation of dust extraction. In this section, the working principle of extracting will be explained, the key design parameters are identified, and the process for the modeling and simulation of the extracting process in the COSMOSFloWorks has been introduced.

3.1 Principle of dust extraction

A cross section of the air chamber of the dust extraction has been illustrated in Fig. 4. During the drilling process on composite materials, the dusts are generated around the drill bit. The clean air is flowed into the air chamber from the gap of the brush between the air chamber and the upper surface of the workpiece. The fan connected to the hose of the outlet generates a lower pressure in the hose. Due to the difference of the air pressure between the inlet and outlet, the air will pass through the air chamber and flow out to the outlet. The dusts join the air flow when the air passes the air chamber. The dusts are finally filtered by the dust collector located between the fan and the air

Fig. 4 Working principle of extracting



chamber. The fan must be capable of generating sufficient pressure difference between the inlet and outlet of the air chamber.

3.2 Modeling of dust extraction in COSMOSFloWorks

CFD helps engineers study many of the issues involved in the analysis of dynamic fluid behaviors. It provides a way to save a great deal of time and money in obtaining the necessary information and assists engineers in designing better quality equipment. The use of CFD makes it possible to eliminate expensive physical prototypes and find serious flaw much earlier in the design process [19]. The COSMOSFloWorks has been selected as an analysis tool in this study. It utilizes a number of automation tools to simplify the analysis process. It is capable of detecting the fluid volume automatically from a CAD part and assembly model, generating the meshes both for fluid and solid regions automatically, improving accuracy with solution adaptive mesh generation, and creating the goal plots to evaluate pressure changes and temperature distribution automatically [19]. In creating a simulation model, the following typical steps are involved in.

3.2.1 Simplified assembly model

The design of the dust extraction has been modeled in the SolidWorks. To reduce simulation time, the model has been simplified in Fig. 5, which consists of six parts, i.e., spindle, drill bit, air chamber, virtual lip, brush, and workpiece. After these parts are assembled together, it forms an encapsulated volume for CFD analysis. The internal lateral surface will be treated as the inlet; the virtual lip represents the area of the hose where the air flows out of the air chamber. The dusts are generated around the axis of the drilling bit. The model can be uploaded directly for the CFD analysis in COSMOSFloWorks.

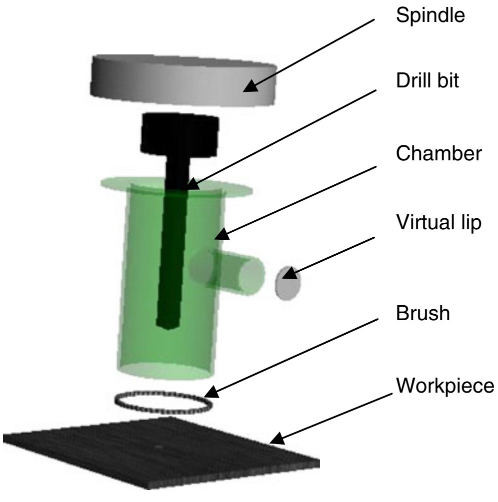


Fig. 5 Explored view of the simplified model

3.2.2 Types of media

Within the computation volume, there are two types of media: the air from the gap of the brush and the dusts generated from composite drilling. The air is directly input from the environment; therefore, the default properties of air fluid in the COSMOSFloWorks can be directly used. The characteristics of the dusts relate to the properties of composite materials. The density of the dusts in the air chamber depends on the drilling parameters. The dusts are mixed with air, and their behaviors can be modeled through the particle studies at the phase of post-processing.

3.2.3 Boundary conditions

Boundary conditions are required anywhere fluid enters or exits the system and can be set as a pressure, mass flow, volume flow, or velocity. Taking into consideration of the air chamber, the following three types of boundary conditions are specified:

(a) The inlet relating to the brush. Air flows into the air chamber directly from the environment; therefore, the corresponding boundary condition can be specified as the given pressure as the surrounding atmosphere.
(b) The outlet relating to the virtual lip. The mass or volume of the fluid flows out of the hose depends on the specifications of the fan. The more power the fan has, the more air flows out of the hose. Therefore, the specifications of the fan can have a

Table 2 The levels of input parameters in the L_9 trials

Trial no.	Levels of input parameters			
	A	*B*	*C*	*D*
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 1 Design parameters and levels

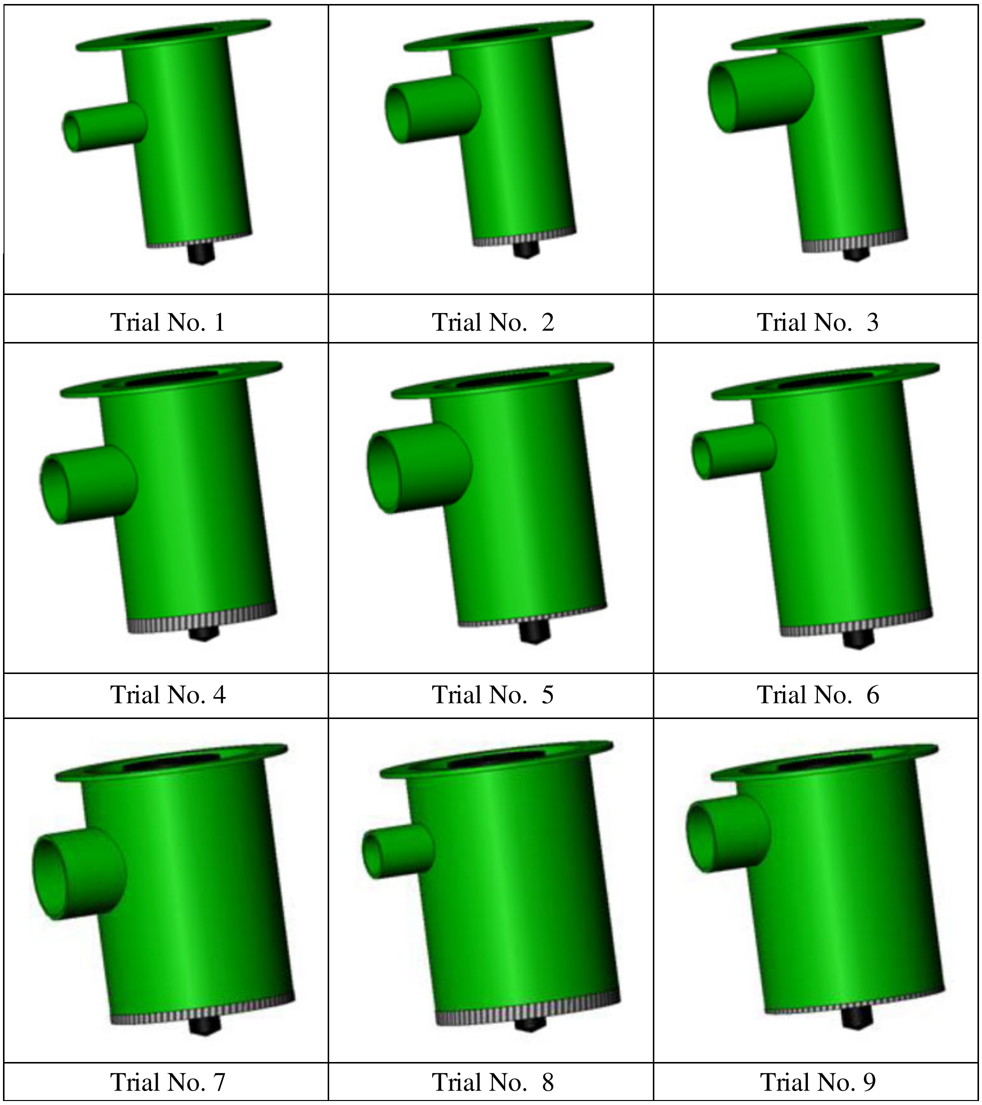
Code	Factor	Levels		
		1 (mm)	2 (mm)	3 (mm)
A	The inner diameter of the air chamber	120	150	180
B	The position of the outlet	130	150	170
C	The hose size of the outlet	50.8	76.2	88.9
D	The gap of the inlet	5	10	15

great impact on the optimization of dust extraction. In this study, it is assumed that the fan extracts the air at the constant speed with 0.5 m^3/s.

(c) The walls relating to the rest of the surfaces. The roughness and humidity of the walls have some impact on the airflow as well. Since the impact is not significant in comparison to the design parameters of the dust extraction, the default setting of wall conditions are applied and remain unchanged.

3.2.4 Analysis goals

Setting goals is essential for the COSMOSFloWorks analysis to focus on the parameters the user is interested. Appropriate setting of the goals also reduces the solving time. Goals can be set throughout entire computational domain, within a selected volume, in a selected surface area, or at given point. In this study, the average pressure drop and air flows over entire computational domain are specifically interested and set as the analysis goals.



Trial No. 1 Trial No. 2 Trial No. 3

Trial No. 4 Trial No. 5 Trial No. 6

Trial No. 7 Trial No. 8 Trial No. 9

Fig 6 The design configurations of the air chamber

Table 3 The results of simulation

Trial no.	Levels of input parameters				
	Ratio of exchange $V_{R,i}$	Normalized exchange rate $\overline{V}_{R,i}$	Pressure drop P_i	Objective f_i	η (dB)
1	208.7553894	0.166259734	0.662555144	0.828814878	1.630849
2	208.7553894	0.166259734	0.289516901	0.455776635	6.824959
3	208.7553894	0.166259734	0.205519862	0.371779596	8.594289
4	125.4522869	0.099914373	0.240447076	0.340361449	9.361193
5	125.4522869	0.099914373	0.22416679	0.324081163	9.786924
6	125.4522869	0.099914373	0.650516654	0.750431027	2.493784
7	84.32500354	0.067159237	0.215426598	0.282585834	10.97699
8	84.32500354	0.067159237	0.650297557	0.717456794	2.884085
9	84.32500354	0.067159237	0.24597582	0.313135057	10.08537

3.2.5 Simulation and post-processing

After the CFD model is established, the COSMOSFloWorks can be run to get the results. In post-processing, the particle study can be conducted to investigate how the air flow influences on the dust extraction. The animation can be automatically generated, which allows the user to observe the process the dusts are extracted by the air flow. The results of the simulations under different parameters can be compared based on the pre-specified design criteria. The design parameters correspond to the best result will be selected as the best solution.

4 Taguchi method for design optimization

Flow dynamics is a complex phenomenon; it is impractical to establish the explicit relations between the design parameters and the criteria of extracting performance. Therefore, the simulation-based approach is applied for the optimization. Note that the CFD simulation is computationally intensive; the Taguchi method can be applied to reduce the number of simulations and obtain a reasonable solution with the minimized computation.

4.1 Design variables and levels

Assume the specifications of the fan are given. In determining the key factors of dust extraction device, the following four design parameters are selected to describe the computational fluid domain and air flow:

- The diameter of the air chamber d_1: It determines the volume of the air involved in the ventilation.
- The diameter of the outlet d_2: It relates to an area where the inside air flows out the air chamber.
- The height of the outlet d_3: It influences the air flow within the air chamber.
- The height of brush d_4: It relates to an area where the outside air flows into the air chamber.

The options of the drill dimension are 9.525 mm (3/8″), 12.7 mm (1/2″), and 15.875 mm (5/8″). Through our primary studies, it is found that the drill dimension has a minor impact on the air flow. Therefore, it has not been treated as the design variable. The following simulation is for the drill dimension with 12.7 mm.

4.2 Design objective

Given the volume of the exchanged air within the certain time period, the performance of the dust extracting can be evaluated based on two criteria, i.e., the exchange rate of the volume $V_{R,i}$ and the pressure drop P_i between the inlet and outlet. The good performance of dust extraction corresponds to the higher exchange rate of the volume and the larger pressure drop between the inlet and outlet. Therefore, the design

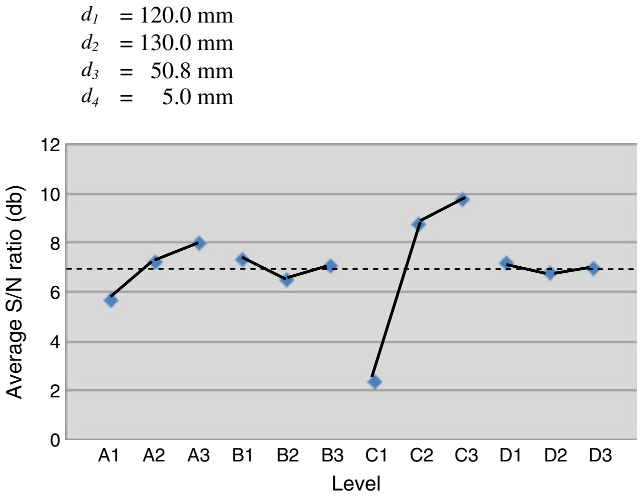


Fig. 7 S/N ratio for the groups

Table 4 The summary of ANOVA for the simulation result

Factor	Levels of input parameters			
	Degree of freedom	Sum of squares	Mean square	Percent contribution
A	2	2.73908	1.36954	7.657443
B	2	0.354183	0.177091	0.990163
C	2	32.59565	16.29783	91.12524
D	2	0.081256	0.040628	0.227161
Total	8	35.77017	4.471272	100

objective f_i is defined based on the normalizations of exchange rate $\overline{V}_{R,i}$ and $\overline{P}_i$, i.e.,

$$f_i = \overline{V}_{R,i} + \overline{P}_i \tag{1}$$

where

f_{i} is design objective

$\overline{V}_{R,i} = \frac{V_{R,i}}{\sum_{i=1}^{n} V_{R,i}}$ is the normalization of the exchange rate $V_{R,i}$

$V_{R,i} = \frac{\text{Extracting volume per second}}{\text{Air chamber volume of design } i}$

$\overline{P}_{R,i} = \frac{P_i}{P_{\text{Atmosphere}}}$ is ratio of the pressure drop of the air flow and standard atmosphere pressure

4.3 Levels of design parameters and orthogonal array

For each of the selected design parameters, three levels have been specified. The corresponding values of the levels for these design parameters have been provided in Table 1.

Based on the Taguchi method, the defined design problem has four factors (i.e., $F=4$) and three levels (i.e., $L=3$). The minimum number of the required trials will be $N_{\min} = (L-1)F + 1 = 9$. As a result, the corresponding nine trails have been listed in Table 2 [10].

Corresponding to Table 1, the configurations of the air chamber CAD model have been illustrated in Table 2, and their design configurations have been illustrated in Fig. 6.

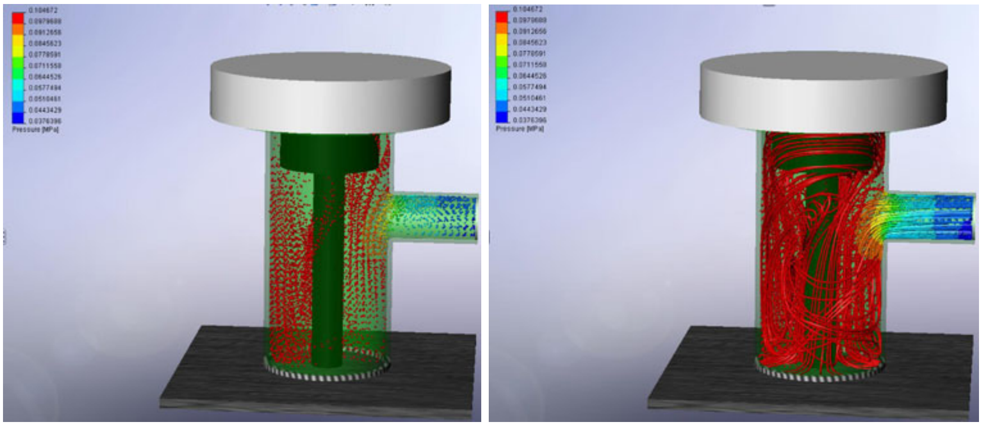
5 Results

The simulation has been conducted in the COSMOSFloWorks, and the results have been provided in the Table 3. Based on the Taguchi method, the signal-to-noise (η) associated with the design objective has been determined as [10],

$$\eta = -10\log\left(f_i^2\right) \tag{2}$$

The ANOVA is applied to identify the significant design factors based on the percentage contribution to the variations of the response. The analysis of average S/N ratio on the four design factors has been illustrated in Fig. 7, and the corresponding sum of square, mean square, and the percent of the contribution have been further determined and provided in Table 4. The most significant design factor C has the percent contribution of 91.12%. It corresponds to the diameter of the hose. Based on the Taguchi method, the best configuration for dust extraction is as follows:

$d_1 = 120.0\text{mm}$
$d_2 = 130.0\text{mm}$
$d_3 = 50.8\text{mm}$
$d_4 = 5.0\text{mm}$



(a) Dust particles in extracting (b) Dust particles and motion trajectories

Fig. 8 Animation of dust extracting. **a** Dust particles in extracting, **b** dust particles and motion trajectories

6 Animation of dust extracting

For the selected design, to visualize the process how the dusts are extracted by the air flow, the particle studies in the COSMOSFloWorks. The particles can be generated by injecting. The properties of the injected particles could be tuned to match the drilling test, i.e., the mass flow is calculated by the actual volume of composite materials determined by (1) the specified drilling parameters, (2) hole dimension, and (3) the sizes of the particles that are measured from the dusts collected from the primary tests. Since the settings of the injected particles have no impact on the calculation of CFD simulation [18], the default value of the mass flow is applied and the size of the particle is set as 3 μm. Figure 8 has shown that two screen captures of the animation, which have illustrated that the particles experience reasonable trajectories from the injection to the outlet, and almost all of the particles have been extracted successfully.

7 Conclusion

Composite materials become more and more popular due to the shortage of energy resources and the global awareness of environment protection. The parts with composite materials need to be machined before they can be assembled into final products. Limited studies have been found on the dust control during the composite drilling. In this paper, three design concepts of dust extraction have been proposed to be used in a dedicated test platform or actual drilling application with an industrial robot. For the sake of generality and robotic automation, the design of dust extraction attached on the machine tool has been further studied. The systematic procedure for the design optimization of the dust extraction is proposed. The COSMOSFloWorks is used to model the air flow in the device, and the Taguchi method is applied to optimize the geometries of dust extraction.

The animation of the optimized design has proven that almost all of the dusts can be captured by the air flow and extracted successfully. Among the four design parameters, the size of the outlet hose has the most significant impact on the performance of the dust extraction. While the analysis of the presented work has focused on a specific design, the proposed procedure is applicable to other designs of dust extraction. Note that the presented optimization is simulation-based and the impact of drilling parameters have not been considered. Our further work is to fabricate the device, take into considerations of more design parameters, and conduct the experiment of composite drilling for validation and improvement.

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