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Velocity Analysis of Barrel Bore Cleaning Device with Abrasive Brush

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After the barrel is fired, the dirt in the barrel will affect the firing performance and service life of the barrel, and it's hard to be removed. It is time-consuming and labor-intensive to clean the dirt manually. However, the existing automatic cleaning methods have poor cleaning effect, and the use conditions and scenes are greatly limited. Based on the rifle barrel with an inner diameter of 105 mm, a cleaning method using a wheeled abrasive brush was proposed. To study the influence of two important dimensions of abrasive brush, namely brush wire diameter and brush wire width, on the running velocity of cleaning device, according to the structural characteristics of abrasive brush, the interaction model between abrasive brush and the barrel bore was established, and then the mathematical model was obtained, which explained the influence of brush wire diameter and brush wire width on the running velocity of cleaning device. Then the influence of the change of two dimensional parameters on the running velocity of the cleaning device was tested in practice. Considering the influence on the reciprocating stroke and velocity of the abrasive brush due to the actual structure of the double-acting cylinder, the speed calculated according to the test results is 1.27 times that that according to the theory, and the obtained mathematical model was modified using MATLAB. The maximum error between the velocities obtained by experimental test and the velocities calculated by using the modified mathematical model was less than 10%. Finally, the cleaning test of barrel bore was carried out. By observing the cleaning effect of abrasive brushes with different parameters, it was determined that the diameter and width of brush wire suitable for barrel bore cleaning was 1 mm and 150 mm, respectively.

Keywords: Barrel bore, Brush wire diameter, Brush wire width, Interaction model, Running velocity

Introduction

After the barrel is fired, the severe environment like high temperature and high pressure would lead to deposition of dirt with complex components such as copper, powder residue and carbon deposition at the grooves and lands of the barrel.[1,2] The dirt could affect the ballistic performance, reduce the quality and shorten the service life of the barrel.[3,4] Therefore, barrel cleaning is very important for barrel maintenance.

Research status

In addition to manual cleaning, there are automatic methods including shock wind tunnel, laser, high-pressure water jet, abrasive flow, abrasive brush grinding and chemical cleaning.[5–12] However, for barrel cleaning, besides cleaning effect, whether in fighting outside or daily maintenance, cleaning velocity is an important indicator that needs to be guaranteed, which would directly decide the cleaning ability of barrels and the supply ability of clean barrels in wartime. At present, manual cleaning wastes too much time and resources, automatic methods are complicated on operating, structural component, and are poor on running velocity and cleaning effect. From the perspective of complexity, operability and adaptability, abrasive brushes are still the most commonly used in barrel cleaning at present.

For cleaning device with abrasive brush in application, there's a device in Britain which brush can rotate driven by a motor, but its size is too large. An electric device in South Korea is short at output scrubbing force and cleaning velocity. Meanwhile, a device in Myanmar uses compressed air is fit with smooth barrel bore, but the effect is unsatisfactory. When it comes to laboratory experiments, some achievements have been made. Tao *et al.* have developed a tube robot which scrubs by driving the brush with a motor in a spiral motion.[13] Zhang & Li have designed a fully automatic barrel cleaning equipment, which softens the dirt by cleaning agent and scrapes it off by steel brush.[14] Nian *et al.* have produced a fully automatic robot with variable diameter, it could suit with barrels with different

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diameter.[15] The three cases above all use electric motivation. The work flow of the device is complicated, the cleaning velocity and the actual effect can't be guaranteed, so they can't be applied in industrial production, and the analysis of the influence on the running velocity of the cleaning device is lacking, so that the velocity can't be determined.

Aiming at the problem that the existing cleaning methods of gun barrel bore are difficult to realize portable automatic cleaning of gun barrel bore and cannot guarantee the cleaning effect, facing the demand of modern shooting weapons for automatic cleaning of gun barrel bore, taking Ø105 mm caliber linear bore gun barrel as the research object, the technological basis and key technologies are studied from the aspects of the structure of automatic cleaning device for gun barrel bore, the analysis of abrasive brush movement speed and the influence of abrasive brush parameters on cleaning effect.

Considering the simple structure of pneumatic actuators and its ability to provide greater scrubbing force, this study put forward a sketch of cleaning barrel using an abrasive brush which is motivated by a cylinder to move back and forth continuously.[16,17] For the structural parameters of abrasive brush will decide the velocity of the device, and that will directly determine the velocity of barrel cleaning, in this study, a mathematical model of the influence of two structural parameters of abrasive brush, which are wire diameter and wire width, on the velocity of cleaning device was established, so as to analyze the velocity of the device from quantity, then verified and corrected the model by experiments.

Materials and Methods

Structure of Barrel Bore

The barrel is a hole with a large depth-diameter ratio, which has many spiral flutes called rifles in it that contains grooves and lands compared with normal holes. This study is oriented to 105 mm rifled barrel, some important sectional dimensions is displayed in Fig. 1, every section has the same shape, but there will be angular deflection due to the spiral structure of each rifling. Each groove has a width of 3.87 mm and a depth of 1.62 mm.

Method of Barrel Cleaning

Automatic cleaning device was used in consideration of large-depth-diameter-ratio feature of the barrel. In the front of the device, there's a double acting cylinder called brush cylinder driving an abrasive brush to move back and force, in order to remove the dirt in the barrel. In the back of the device, there's a locking unit to locate the device along the axis of the barrel, and to protect the device from vibrating heavily when the abrasive brush is moving. The sketch to clean is shown in Fig. 2. Compared with existing device, this device is easier on structure.

Structure and Parameters of Abrasive Brush

The brush wires of the abrasive brush are arranged in clusters in straight rows, and SiC abrasive is added to obtain better cleaning effect. The bristle tufts are arranged with a certain density, so that the abrasive brushes can clean grooves more effectively.

For wheeled abrasive brushes, there are many factors that affect their cleaning speed and cleaning effect, including material, diameter, and width of the brush wire, the number of brush tuft, and the difference between the outer diameter of abrasive brushes and the inner diameter of barrel. In this article, under the case of the number of brush tuft is determined, for a certain brush whose material and outer diameter are determined. The force acting on the abrasive brush is mainly impacted by two dimensions, which are wire diameter d_1, and wire width B, as shown in Fig. 3.

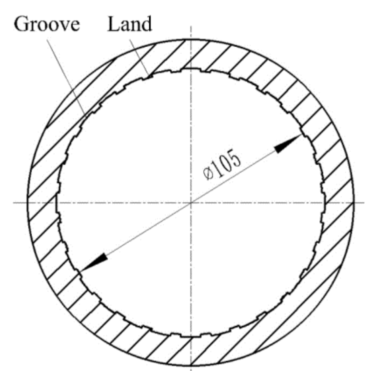

Fig. 1 — Section shape and main dimensions of barrel bore

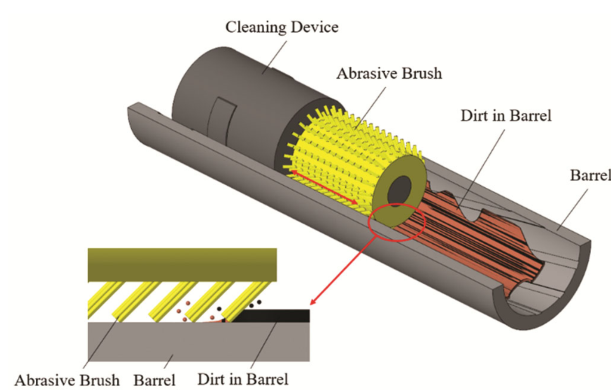

Fig. 2 — Method of barrel bore cleaning

Force Analysis of Abrasive Brush during Running

Force Analysis of Single Brush Wire

The diameter of the abrasive brush is larger than that of the barrel, so the brush wire will bend when it comes into the barrel bore, so the brush wire can be simplified to a cantilever beam whose one end is fixed on the brush wheel.

The brush will make a spiral motion along the rifles in the barrel. Let the direction of barrel axis be the x direction, the positive pressure direction of the barrel bore on the brush wire be the y direction, the normal line of plane xOy be the z direction of the spatial rectangular coordinate system so that to simplify the force analysis of the brush wire, and the Instantaneous velocity direction of the brush wire endpoint is set to the e direction.

The mass of a single brush wire can be neglected, so the impact of gravity to a brush wire needn't be considered. The force to a single brush wire received by the barrel bore is shown in Fig. 4(a).

The output force F_0 of the brush cylinder is shown in as Eq. (1):

$$F_0 = \frac{\pi}{4} d^2 p \qquad \text{... (1)}$$

where, F_0 is the output force of the brush cylinder, d is the diameter of piston rod of brush cylinder and p is the air source pressure.

To obtain the resilience of brush wire due to bending deformation in direction e, the brush wire was simplified to a link which has a fixed end and a free end, so that the force of a single brush wire can be separated to two parts displayed separately in Eq. (2) and Eq. (3), one is the resistance of brush wire, called F_c', due to bending deformation in direction e which is related to the length l and the deformation w_B of a single brush wire, the other is the friction from barrel bore, called f', as the brush wire moving, which is related to the friction coefficient μ and the normal pressure $F_\perp$' of barrel bore.

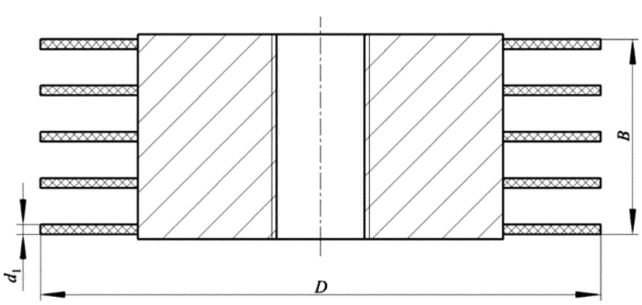

Fig. 3 — Size factors affecting the force of abrasive brush

$$F_c' = \frac{3EIw_B}{l^3}, \quad F_{cx}' = F_c \cos\theta \qquad \text{… (2)}$$

$$f' = \mu F_\perp', \quad f_x' = f' \cos\theta \qquad \text{… (3)}$$

where, F_{cx}' and f_x' are the components of F_c' and f' along the axis of barrel respectively, and θ is the helix angle of rifles in barrel.

Force Analysis of the Whole Abrasive Brush:

As shown in Fig. 4(b), the brush is acted by the output force F_0, the components of the friction f and the resistance F_c, which are shown separately in Eq. (4) and Eq. (5) and are related to the number of tuft k and that of brush wire per tuft n in x direction when it extends.

$$f_x = nkf_x' \qquad \text{… (4)}$$

$$F_{cx} = nkF_{cx}' \qquad \text{… (5)}$$

where, f_x and F_{cx} are the components of the friction f and the resistance F_c in x direction respectively.

Running Velocity Analysis of Device

Based on force analysis of the whole abrasive brush in Fig. 5, using Newton's second law formula can get the acceleration during the extension process of the piston rod of brush cylinder like Eq. (6):

$$F_0 - F_{cx} - f_x = ma \qquad \text{… (6)}$$

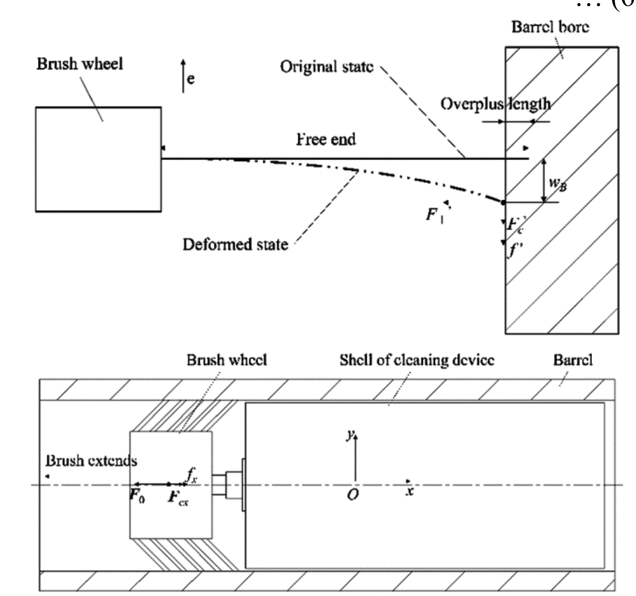

Fig. 4 — Force analysis of: (a) brush wire in bending plane, (b) abrasive brush when it protrudes

where, m is the mass of abrasive brush used on the cleaning device, a is the acceleration of the brush.

If the abrasive brush does linear motion with constant acceleration like Eq. (7), and s is the stroke of the piston rod of brush cylinder, the time of the brush extension t_1 can be obtained from Eq. (8).

$$s = \frac{1}{2}at^2 \quad \dots (7)$$

$$t_1 = \sqrt{\frac{2sm}{F_0 - F_{cx} - f_x}} \quad \dots (8)$$

The pulling force provided by the brush cylinder isn't enough to change the direction of bending of the brush wire when the piston rod retracts. In this condition, the rest part of the device will move towards the abrasive brush driven by the brush cylinder. The time which the piston rod can be fully retracted t_2 can be calculated using Eq. (9) under the condition that the mass of the device except the abrasive brush m_0 is 20 kg, and the stress area of the cavity with rod is a quarter of that of the cavity without rod for a standard cylinder.

$$t_2 = \sqrt{\frac{8sm_0}{F_0}} \quad \dots (9)$$

The brush cylinder was selected and some constant parameters of the abrasive brush were defined as Table1 according to the working conditions.

According to the parameters in Table1 and Eqs (1 – 9), the average velocity v of the cleaning device when it runs under the influence of the brush wire diameter d_1 and the brush width B can be established as Eq. (10).

$$v = \frac{3}{\sqrt{\frac{0.1m}{755.0 - 0.394nkF_{\perp}' - 0.305nkd_1^4}} + \sqrt{\frac{8}{755}}} \quad \dots (10)$$

Correction to the Running Velocity of Device

Instead of a standard uniformly acceleration motion, the running velocity of the piston rod is approximately like the form of "acceleration-uniform-deceleration", so the Eq. (10) needs to be corrected in order to obtain the real running process of the brush cylinder. The acceleration-time curve of the piston rod of brush cylinder was measured when it was running without any loads by Donghua IEPE piezoelectric acceleration sensor.

The acceleration of the piston rod with no loads was collected and shown in Fig. 5 (a) under the sampling frequency of 2 kHz.

The curve was integrated to obtain the displacement-time curve of the piston rod. However,

Table 1 — Constant parameters information

Parameter	Value
Length of brush wire l, mm	20
Air source pressure p, MPa	0.6
Diameter of brush cylinder d, mm^2	40
Stroke of piston rod of brush cylinder s, mm	50
Elastic modulus of nylon E, GPa	1.4
Frictional coefficient between nylon and steel, μ	0.4

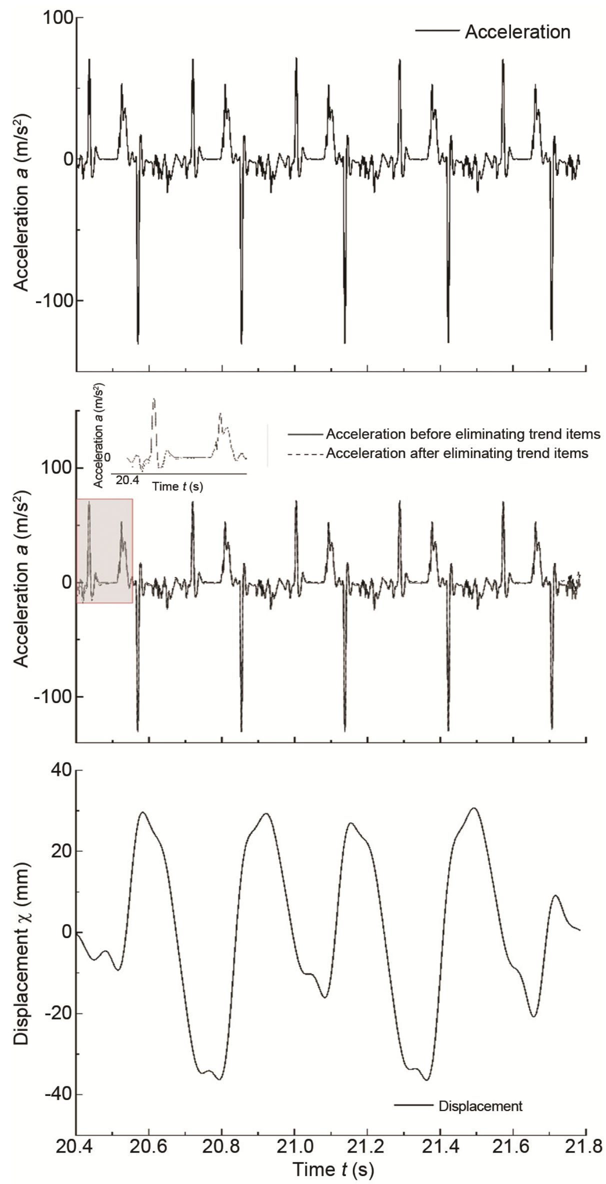

Fig. 5 — Experimental curves of brush cylinder piston rod: (a) acceleration-time curve, (b) comparison of local acceleration curves before and after elimination of fifth-order trend item, (c) displacement-time curve

the acceleration curve directly obtained contains lots of interference information due to the zero drift of the sensor and external environment.[18] To remove these interference, least-square method was leaded to process the obtained data by eliminating trend items so that to get purer information of acceleration.[19]

This operation can be directly done by function polyfit (t, a, m) in MATLAB, where t is time column vector, a is acceleration column vector and m is the rank of the polynomial to be fitted. It was found through practice that the acceleration curve would have great changes like Fig. 5(b) when m = 6, and the changes would more and more insignificant after m > 6. So for data processing in this study, m = 6.

In consideration that frequency domain integration can usually obtain more accurate data than time domain integration, Fourier transform was used to carry out the second integral on the acceleration-time curve after eliminating trend items so that to obtain the corresponding displacement- time curve.[20]

Function FFT and iFFT were used in MATLAB to perform fast Fourier transform and inverse fast Fourier transform on the acceleration-time curve and displacement-frequency curve separately, and the displacement-time curve was finally obtained as Fig. 5(c).

Then it could be calculated that the actual average velocity of the piston rod was 21.05 m/min, 1.27 times less than that calculated from the data in Table 1. So correction factor c was introduced and let c = 1.5 in consider that the structure of the cylinder and the obstructive effect on the abrasive brush by the edge of rifles in barrel would make the stroke of the piston rod shorter than its theoretical value, so that the Eq. (10) was corrected to Eq. (11) as

$$v = \frac{3/c}{\sqrt{\dfrac{0.1m}{755.0 - 0.394nkF_{\perp}' - 0.305nkd_1^4}} + \sqrt{\dfrac{8}{755}}} \quad \ldots (11)$$

But if the value of F_0-F_{cx}-f_x is no more than 0, it means that the resistance to the abrasive brush is greater than the output force of the brush cylinder due to the parameters of the brush selected, and the brush cylinder could not drive the abrasive brush to extend forward, the velocity of the cleaning device would be 0 in this situation.

Results and Discussion

To ensure the other parameters except the wire diameter and wire width of the abrasive brush are consistent, the abrasive brushes used in this study are all wheeled brush with a total outer diameter of 115 mm, and the abrasive particles are SiC with the size of 120 #.

The wire diameter and wire width of each brush were shown in Table 2. In this table, brush No.1, 4, 5, 6, 7 were used to explore the influence of the wire diameter on the running velocity of the cleaning device, and brush No.1, 2, 3 were used to explore the influence of the wire width on the running velocity of the device.

Measurement of the Positive Pressure $F_{\perp}$' of the Brush Wire Bending on the Barrel Bore

The layout of the measuring device was shown as Fig. 6 including a mobile slide, a piezoelectric transducer and abrasive brushes with different wire diameters. The free length of the front end of the brush wire was 20 mm, and the front end was just right in contact with the force measuring plane of the piezoelectric sensor before measurement.

The brush wire touched the force measuring plane of the sensor and began to bend as the slide

Table 2 — Wire diameter and width of each abrasive brush

Brush number	Wire diameter d_1, mm	Wire width B, mm
1	0.5	100
2	0.5	120
3	0.5	150
4	0.8	100
5	1	100
6	1.2	100
7	1.5	100

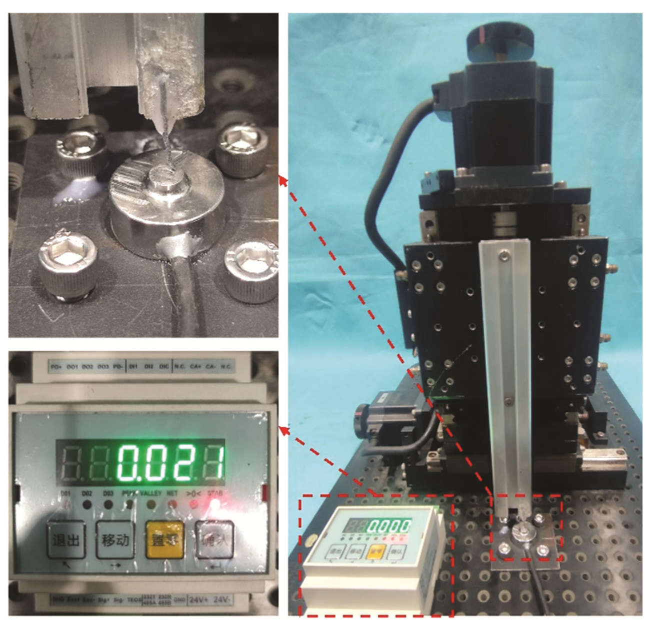

Fig. 6 — Displacement-time curve of brush cylinder piston rod

descending. The value of the sensor was read after it became steady in the condition that the descending length of the slide was 5 mm, and the value was the positive pressure of a single brush wire bending on the barrel bore.

The positive pressures of a single brush wire with diameters of 0.5, 0.8, 1.0, 1.2, 1.5 mm were measured separately and the values were shown in Table 3, the number of brush wire n that each cluster contains with different brush diameters were also shown in this table.

The mass of abrasive brushes *m* with different brush widths and the corresponding number of brush cluster *k* were shown in Table 4.

Verification of Running Velocity of the Cleaning Device

The running velocities of the cleaning device under different wire diameters were calculated using Eq. (11) and the parameters of Table 1 to Table 4. Fig. 7 shows the calculated results and the practical results corresponding using the abrasive brushes referred in Table 2. As the wire diameter increasing, the error of the running velocities measured rose first and then fell.

The running velocities of the device under different wire width were calculated using the same method. Fig. 8 shows the calculated results and the practical results corresponding using the abrasive brushes referred in Table 2. As the wire width increasing, the error of the running velocities measured rose monotonically.

Evaluation of Cleaning Effect of the Cleaning Device

Due to the limited space in the barrel bore, the cleaning effect of the barrel bore after cleaning was observed by endoscope. The size and focal length of the selected endoscope should be small enough to ensure that it can go deep into the bore of the barrel and take clear photos. Firstly, the specific position in the barrel was marked before cleaning, observed by endoscope and recorded by taking photos. After the cleaning is completed, the same position is photographed and recorded again, and the distribution of dirt in the two photos is compared, so that the effect of cleaning the barrel bore with abrasive brushes with corresponding parameters can be evaluated.

Used the abrasive brushes listed in Table 2 to clean the barrel bore, and observed the cleaning effect. The cleaning process of each abrasive brush was carried out separately, that is, different abrasive brushes were used to clean different barrel bores, thus avoiding the

Table 3 — Bending positive pressure and n value of wire brushing with different wire diameters

Wire diameter d_1, mm	Positive pressure $F_{\perp}$', N	Number of brush wire of each cluster *n*
0.5	0.01	20
0.8	0.01	16
1	0.02	12
1.2	0.05	10
1.5	0.08	8

Table 4 — Mass and k value of abrasive brushes with different wire widths

Brush width *B*, mm	Mass of abrasive brush *m*, kg	Number of brush cluster *k*
100	0.55	224
120	0.68	252
150	0.82	304

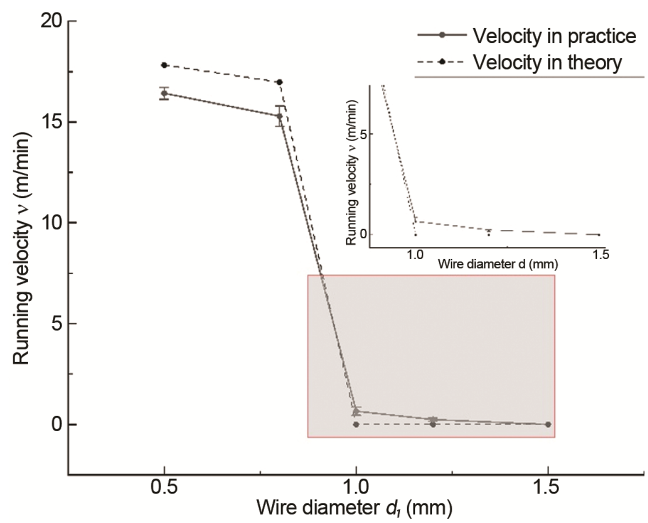

Fig. 7 — Brush wire diameter-device running velocity curve

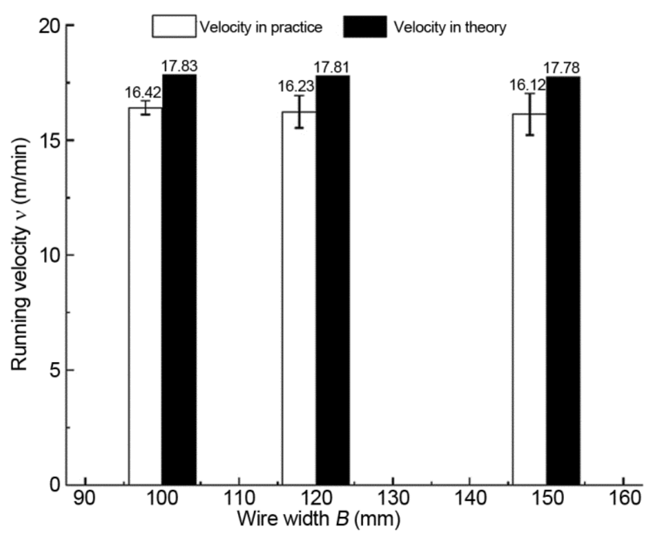

Fig. 8 — Brush wire width-device running velocity curve

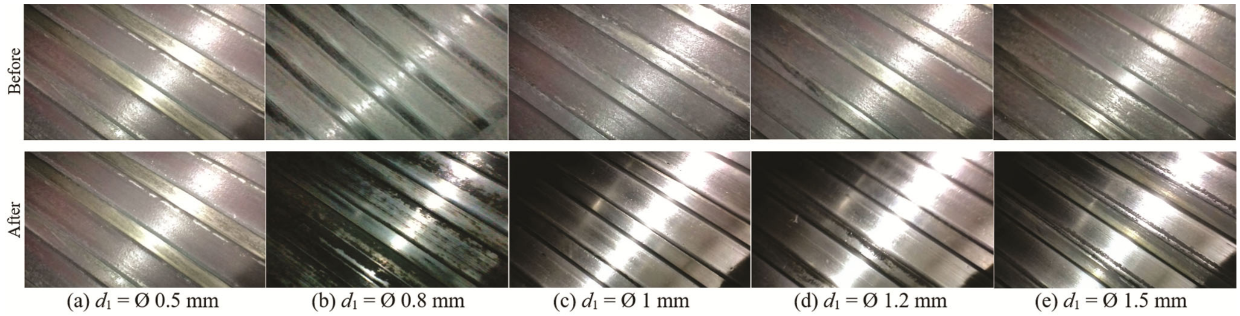

Fig. 9 — Variation of dirt distribution with d_1 before and after barrel bore cleaning at: (a) d_1 = 0.5 mm, (b) d_1 = 0.8 mm, (c) d_1 = 1 mm, (d) d_1 = 1.2 mm, (e) d_1 = 1.5 mm

interference of the previous abrasive brush on the cleaning effect of the following one.

When observing the influence of wire diameter on cleaning effect, let the cleaning time of all abrasive brushes was 1 h, and each brush had a wire width of 100 mm.

The situation of dirt distribution before and after using abrasive brushes with different wire diameters are shown in Fig. 9. With the increase of wire diameter, the residual dirt after cleaning decreased first but then increased.

The larger the diameter of brush wire, the greater the friction force of the abrasive brush in the movement process, the more effective the abrasive brush is in scraping dirt and the better the cleaning effect is. However, if the diameter of brush wire is too large, the deformation of each brush wire of abrasive brush may be irregular, resulting in a gap in the cleaning process, which is the area where the brush wire is avoided due to deformation during the movement of abrasive brush, resulting in uneven cleaning effect. For this test, the cleaning effect is the best when the diameter of brush wire is Ø1 mm

When observing the influence of wire width on cleaning effect, let the cleaning time of all abrasive brushes was 1 h, and each brush had a wire diameter of 0.5 mm.

The situation of dirt distribution before and after using abrasive brushes with different wire width is shown in Fig. 10. The residual dirt after cleaning decreased with the increase of wire width.

According to the structural characteristics of the cleaning device, when the brush wire width is greater than the cylinder stroke, the cleaning device will produce overlapping cleaning effect on the barrel bore during operation, and when the cylinder stroke is constant, the greater the brush wire width, the greater the overlapping cleaning effect and the better the cleaning effect on the barrel bore.

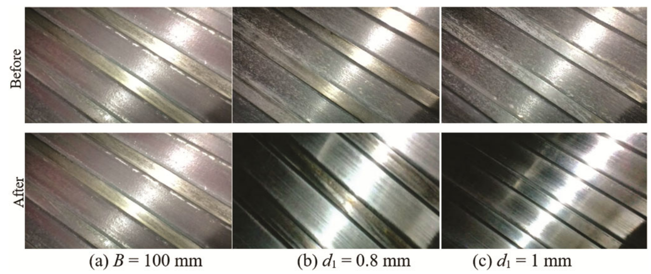

Fig. 10 — Variation of dirt distribution with B before and after barrel bore cleaning at: (a) B = 100 mm, (b) d_1 = 0.8 mm, (c) d_1 = 1 mm

Conclusions

The study developed and validated a pneumatic abrasive-brush barrel cleaning device, demonstrating that brush wire diameter and width are key factors governing its running velocity and operational feasibility. Increasing these parameters raises resistance and degrades velocity stability, with a critical transition observed when the wire diameter approaches 1 mm, beyond which forward motion becomes difficult. The results highlight the importance of appropriately matching brush structural parameters with actuator output capability to ensure reliable cleaning performance.

Limitations arise from measurement uncertainties in piston acceleration due to noise, vibration, and incomplete stroke, which may affect the precision of velocity characterization. Future work should therefore focus on improved signal processing methods, such as sampling signal transformation and frequency-domain integration, to obtain more accurate dynamic responses. In addition, the spiral rifling geometry suggests that further optimization of brush geometry and wire arrangement is necessary. The proposed device shows strong potential for cleaning deep hole components, including aircraft turbine shafts, oil and gas pipelines, and nuclear power plant pipelines.

Conflict of Interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and is not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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Reference

1 Wang M, *Study on Ultrasonic Cleaning Mechanism of Gun Bore Attachment*, Master thesis, Harbin Institute of Technology, Harbin, China, 2021, http://doi.org/10.27061/d.cnki.ghgdu.2021.003579.

2 Yu P, Jiang D, Zhang B & Zhang Y, Microcomputer transformation of barrel inner diameter measuring instrument based on VB, *Tool Eng*, **42(1)** (2005) 62–64, http://doi.org/10.3969/j.issn.1000-7008.2005.01.023.

3 Li X, Zang Y, Mu L, Lian Y & Qin Q, Erosion analysis of machine gun barrel and lifespan prediction under typical shooting conditions, *Wear*, **64(05)** (2020) 444–445, https://doi.org/10.1016/j.wear.2019.203177.

4 Wu B, Liu B, Zheng J, Wang T, Chen R, Chen X, Zhang K & Zou Z, Strain-based health monitoring and remaining life prediction of large caliber gun barrel, *Measurement*, **36(122)** (2018) 297–311, http://doi.org/10.1016/j.measurement.2018.02.040

5 Liu Q, Liu Z & Qiu J, A summary of gun bore wiping technology, *Def Manuf Technol*, **02(01)** (2010) 63–67.

6 Zhou R & Ni C, Design of reciprocating vibration penumatic cleaning robot for bore of small caliber antiaircraft gun, *Mach Electron*, **39(03)** (2021) 55–59.

7 Hong C & Yang J, Cleaning method of gun barrel in shock wave wind tunnel, China Patent CN 102698991, Institute of Mechanics, Chinese Academy of Sciences, PRC, 3 October 2012.

8 Zhao M, Xie J, Zheng D, Wu H, Ji D & Zhang G, Laser cleaning device for gun bore, China Patent CN 206824323 Shaanxi HuiZhiDaQing photoelectricity technology co., ltd, PRC, 2 January 2018.

9 Cao G, Liu C & Wu Y, Research on the carbon deposition cleaning technology in gun bore and its application based on high pressure water jet, *J Shenyang Aerospace Univ*, **39(04)** (2022) 27–36, http://doi.org/10.3969/j.issn.2095-1248.2022.04.004.

10 Hao P, Zhang Y, Dong Z & Li Y, AFM & its application in cleaning of the abdominal wall of artillery, *Manag Dev*, **23(04)** (2018) 119–120.

11 Zhu R, A study on the mechanism of eliminating residual copper scale, *Corros & Prot*, **26(03)** (2005) 112–113+119, http://doi.org/10.3969/j.issn.1005-748X.2005.03.007.

12 Zhang K, Wu B & Yang X, Research progress in cleaning of barrel adhesiveness residue, *New Chem Mater*, **43(07)** (2015) 7–8.

13 Tao W, Liao K, Feng H & Qian L, Design of portable gun tube scrubbing robot, *J Nanjing Univ Sci Technol*, **35(04)** (2021) 484–488, http://doi.org/10.3969/j.issn.1005-9830.2011.04.012.

14 Zhang Y & Li Y, Automatic cleaning device for salute gun barrel,*China Sci Technol Panor Magaz*, **16(12)** (2017) 29–30, http://doi.org/10.3969/j.issn.1671-2064.2017.12.021.

15 Nian H, Hao Y, Zhang J & Chang J, Simulation and analysis of mechanical characteristics of diameter changing mechanism of gun bore cleaning robot, *Ele-Optic Technol Appl*, **35(05)** (2020) 81–84, http://doi.org/10.3969/j.issn.1673-1255.2020.05.014.

16 Ye H, Konyo M & Tadokoro S, Design and analysis of a pneumatic high-impact force drive mechanism for in-pipe inspection robots, *Adv Robot Int J Robot Soc Japan*, **30(19)** (2016) 1260–1272, http://doi.org/10.1080/01691864.2016.1205511.

17 Xu S, Xia Y, Li H, Zhang D & Fan Y, Discussion on automatic transformation of gun barrel scrubbing device, *Mod Ind Econ Inf*, **11(01)** (2021) 60–61+68, http://doi.org/10.16525/j.cnki.14-1362/n.2021.01.25.

18 Fang W, Wu J, Yang K & Dai Y, Analysis of causes of zero drift of piezoelectric shock sensor and zero drift suppression, *J Astronaut Metrol Meas*, **42(04)** (2022) 43–48+55, http://doi.org/10.12060/j.issn.1000-7202.2022.04.08.

19 Zhang J, Zheng Q, Yang Y & Meng X, Research on detrending method of MEMS accelerometers' signal in shock measurements, *Instrum Anal Monit*, **03** (2022) 26–34, http://doi.org/10.3969/j.issn.1002-3720.2022.03.007.

20 Wu Y, Wang Z & Hu X, The method of vibration singal frequency domain integral based on Matlab, *Proc 10th Nat Annual Conf Nondestruct Test* (Nanchang, China) 2013, 20–24.