DESIGN OF A SONIC DRILL BASED ON VIRTUAL PROTOTYPE TECHNOLOGY

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ABSTRACT

Sonic drilling is a novel sampling technology applied in many fields. Based on *SolidWorks* software, a dynamics virtual prototyping is utilized to develop a physical sonic driller by demonstrating collision detection and optimizing overall layout and key component structures. Key hydraulic and structural parameters are optimized using a mathematical model. Search for the optimized parameters and operating conditions for this multi-body mechanical system is conducted experimentally. The practical results show that the virtual prototype technology not only shortens the design cycle but also improves the quality of the conventional design. The new sonic driller designed by this method is both environmentally friendly and smarter.

Keywords: Sonic vibration; Drilling; Virtual Prototype; Mathematic model.

CONCEPTION D’UN APPAREIL DE FORAGE PAR VIBRATIONS BASÉE SUR LA TECHNOLOGIE DU PROTOTYPAGE VIRTUEL

RÉSUMÉ

Le forage sonique est une nouvelle technologie d’échantillonnage utilisée dans plusieurs domaines. Basé sur le logiciel *SolidWorks*, un prototype dynamique virtuel d’échantillonnage est utilisé pour développer un appareil de forage par vibrations, en affichant la détection de collision, l’optimisation du schéma général et ses éléments structurels clés. Les paramètres-clés hydrauliques et structurels sont optimisés à l’aide d’un modèle mathématique. La recherche des paramètres optimisés et des conditions opérationnelles pour ce système mécanique multi-corps est expérimenté. Les résultats montrent que la technologie de prototypage virtuel, non seulement diminue le cycle conceptuel, mais améliore aussi la conception conventionnelle. Le nouvel appareil de forage par vibration, conçu par cette méthode, est à la fois sans danger pour l’environnement et plus rationnel.

Mots-clés : vibration sonique; forage; prototype virtuel; modèle mathématique.

NOMENCLATURE

p_1	vertical forces on right side track, N
p_2	vertical forces on left side track, N
b	sonic drill width， m
m	sonic drill weight, kg
e	offset, m
h	gravitational center height, m
F	traction force, N
f	rolling resistance force, N
N	ground support force, N
Δp	hydraulic pressure, MPa
V	driven hydraulic motor discharge, m^3/r
r	driving wheel radius, m
F_z	driving force, N
L	cylinder length, m
M	mast weight, kg
L_z	distance between gravity center and hinge point of the mast, m
F_y	vibration force at the drilling direction, N
m	single eccentric shaft mass, kg
$\boldsymbol{e}$	shaft eccentricity, m
D_m	single high speed hydraulic motor discharge, m^3/r
Q	single high speed hydraulic motor flow, m^3/s
a_0	ground acceleration, m^2/s
M	vibration system mass, kg
m_0	drill pipe weight per meter, kg/m
l	drilling string length, m
$Q_k(x, x)$	non-linear spring and damping force expression, N
x	vibration amplitude displacement, m
c_ε	equivalent damp coefficient
k_ε	equivalent spring coefficient. fuel consumption (kg/kWyr)
β	slope angle
θ	mast angle
γ	cylinder angle

1 INTRODUCTION

Sonic drilling is a new type of sampling technology used in archeological investigations, environmental sampling, geothermal heat loop installation, groundwater monitoring, mineral sampling, soil sampling and water well installation, etc. [1, 2]. Working without water, it performs especially well in arid regions and unconsolidated formations.

The drilling technique has been commercialized successfully in U.S. in 1960s [3]. It is considered by one of its inventors, Ray Roussy [3], as to be the only true innovation to come to the drilling industry since the Chinese invented cable tool drilling some 3000 years ago. In 1985, a current division of Boart-Longyear [3] became the first to use this technique for environmental drilling and it is now widely adopted in construction industry, where strong regulatory and environmental restrictions are enforced [4].

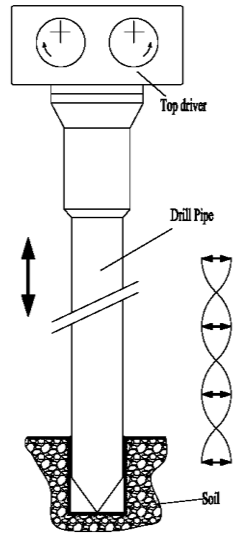

Fig. 1 Principles of sonic drilling processing

Sonic drilling is driven by vibration (0-200Hz) transmitted from the top driver by two balance rollers [5], which ensure the vibrations are transmitted vertically down to the bit. The frequency can be adjusted to achieve maximum penetration rate by matching the natural resonance frequency of the drill string as shown in Fig 1.The string is vibrated by a hydraulically powered drill head at adjustable frequency. In order to prevent the drill joint from unscrewing, there is a hydraulic motor rotating slowly on the top driver. Normally, the slow rotation of the drill string can distribute energy uniformly and prevent uneven bit wear in harder formations such as sandstone, slate, limestone and shale. Resonance provides high energy to the bit, which displaces the particles laterally in soil and fluidizes the soil near the bit to increase drilling speed [6]. The oscillator is equipped with two eccentric counter-rotating balance weights, or rollers, which are timed to direct full vibration at 0º and 180º, while a damper and a spring system in the top driver isolates vibration from the rest of the machine.

A dual cased system driven by high frequency mechanical vibration is designed to extract continuous core samples, or simply to advance casings for grout holes. The outer casing can be advanced at the same time as the core barrel and inner drill pipes, covering them, or to collect the undisturbed core sample being pulled out of the hole [4] after the core barrel moves forward. Depending on the type of ground, levels of surface contamination, and the sampling objectives, the core barrel advancement can range from 0.2 to 9.0 mm in increments.

Sonic drilling is not suited to deep hole drilling. Rather, it is capable of collecting highly representative samples and excellent sample recovery in unconsolidated material formation. Commercially available sonic drillers in general have complicated features such as air spring isolator assembly, synchronization belt and cooling system. These make the sonic driller relatively expensive, and add significant costs in preventive maintenance and repairs for maintaining the sonic system in peak working condition [**7**]. So it is of interest to simplify and improve the mechanical design.. Sonic drill consists of four main components: a top driver, a drilling mast, a rig base and a hydraulic system. These components are ill suited to traditional 2D drawing tools which would be inefficient [8] and tedious [9,10]. Any local modification will lead to multiple modifications on the system, which requires the attention of an experienced designer.

Virtual prototype technology can reduce the cost of the product development through design and analysis with CAD [11]. Parts and layout of the drill can be designed and adjusted repeatedly by virtual prototype technology to cut down the development cycle [12, 13], and reduce unnecessary cost [14]. The

3-D model can then be used to develop further optimization simulations in a virtual environment. Dynamic virtual prototyping was carried out using *SolidWorks*. At the stage of virtual prototype, assembly process visualization for sonic drill was used to detect collision, optimize the overall layout and establish the structure of the key components. The key hydraulic parameters and structure parameters were optimized and determined by a mathematical model for the sonic drill. The physical prototype was manufactured based on the virtual prototype with optimized parameters. Operating characteristics of the sonic drilling methods were studied experimentally, which provides valuable raw data to further develop the drill and other multi-body mechanical systems.

This paper is arranged as followed: Section 2 describes the mechanical design of the sonic drill. Section 3 is devoted to mathematic modeling of the sonic drill used to optimize the key components. Finally, Section 4 presents the description of a sonic drill prototype and its experimental validation.

2 SONIC DRILL DESIGN

2.1. Design Objectives and Parameters

As is shown in Fig. 2, a sonic drill is composed of top driver, drilling mast, rig base and hydraulic system. Top driver is driven by hydraulic high speed motors which transmit high frequency oscillating motion to the vertical drill. Drilling mast is the track of the top driver, where there is a hydraulic cylinder to exert downward force on the drill in addition to bit weight. Hydraulic system is the transmission device which converts the mechanical energy to the hydraulic potential energy to drive the sonic drill. All of the sub-system and parts are fixed on the rig base which is self-propelled over short distance.

To meet the demand of environmental sampling and engineering exploration to depths of 40 meters, the design features the integration of four major subsystems. The design parameters are listed in Table 1.

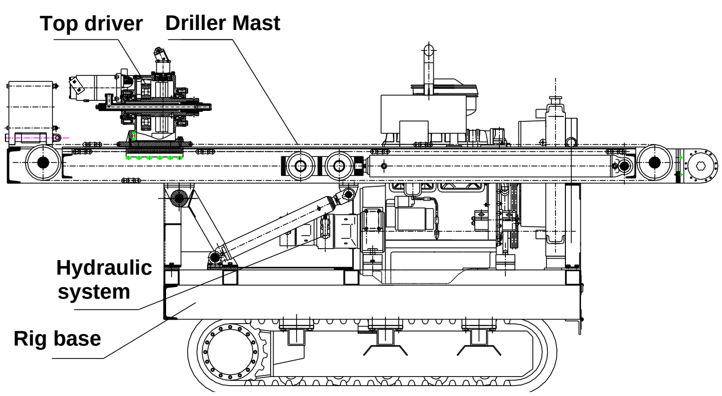

Fig. 2 Structure of sonic drill

Table 1 The design parameters

Items	Parameters	Items	Parameters
Max Vibration Drilling Depth	40m	Max Rotation Drilling Depth	150m
Vibration Frequency	0-200Hz	Maximum Torque	2000N·m
Hydraulic Pressure	21MPa	Power	131kW
Output Force @200Hz	160kN	Feed Stroke	3m
Max Down Force	25kN	Max Pull Back	50kN

2.2. Virtual Prototype Modeling of Top Driver

The valve assembly distributes hydraulic fluid to the two hydraulic motors. When the top driver is vibrating at 5-200 Hz and exerting the pressure on bit by hydraulic cylinder in the mast, the energy is transferred from the mast to the underground core. The joint of the pipe is hollow for the mud flow under some special (no-dry) drilling operations.

The top driver is composed of following parts, oscillation hydraulic motors, a rotation hydraulic motor, a hydraulic valve assembly, a support frame, vibration isolator, an eccentric component, an oscillation body and drilling joint, etc. The standard components such as a hydraulic motor, a hydraulic valve assembly, a vibration isolator and a drilling joint should be modeled first due to geometrical information. The traditional air spring isolator is complicated, so it is replaced by a pair of ring-type metal rubber isolators. Then others will be manufactured following the main parameters from the standard components. Some processing inputs should be determined by field experience. The virtual prototype of a sonic top driver is shown in Fig. 3(a)**.**

Two oscillation hydraulic motors are necessary to guarantee that there is no lateral vibration to avoid damage of the drilling parts. Unavoidable manufacturing and assembly error leads to unstable torque on the two eccentric shafts, hence variations in flow and inlet pressure to the two motors. This problem is solved with a simple synchronizing mechanism to balance the loads of two motors, shown in Fig. 3(b), composed of a simple arrangement of pulleys (two synchronous rollers and three pinch rollers) and a two-sided toothed (timing) belt.

In terms of the hydraulic system, the main system parameters can be used to select the standard hydraulic units. The size of the main components such as the diesel engine, the fuel tank, the hydraulic fluid tank, and the hydraulic operation platform, will be laid out according to their weights on the rig base to avoid unbalance, shown in Fig. 3(d) and Fig. 4. Near the hole is fixed the hydraulic operation platform.

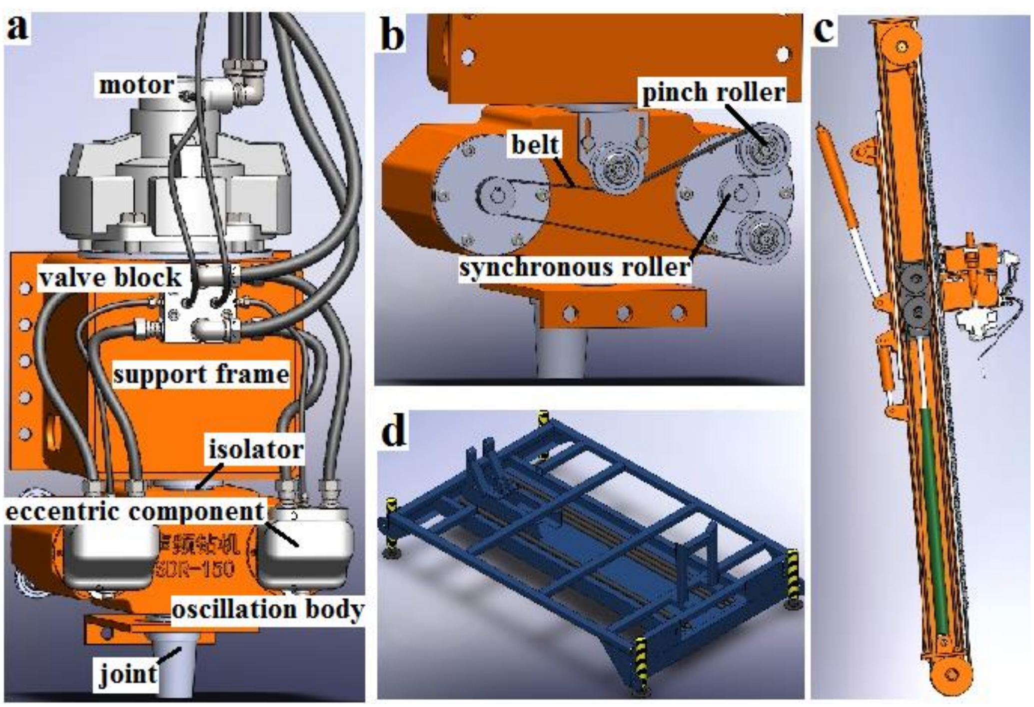

Fig. 3 Virtual prototype of a sonic driller

Other sub systems consist of complex structures, such as drilling mast, hydraulic system and rig base. As is shown in Fig. 3(c), the virtual prototype is built in a certain sequence. Firstly, the width of the drilling mast must be determined according to the mounting plate of the top driver and the steel used. Based on the total design parameters, the main size of the drilling mast then can be calculated. The rest of the parameters can be independently defined by the designer.

2.3. Assembly, Analysis and Optimization of the Sonic Driller

In the process of virtual prototype modeling, the sonic driller is functionally broken into four subsystems: a top driver, a drilling mast, a rig base and a hydraulic system. Each can be simultaneously decomposed into hundreds of parts. After all of the single three-dimensional parts virtual prototype model are built, the sub systems can be assembled to form independent block.

Interference detection is to check the relative position between the subsystems and others [15]. Any mistakes during designing and assembling will be corrected repeatedly. For example, the top driver will be moved on the mast within the designing limits in a virtual environment to check whether there are any mismatches among components and then modify them as necessary.

The whole sonic driller can be carefully adjusted to a suitable general assembly, shown in Fig. 4. Additionally, all three-dimensional models on the sonic driller are represented as two-dimensional engineering drawings to be used in manufacture.

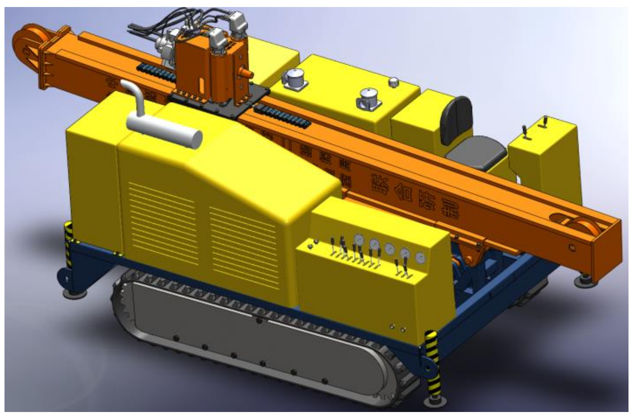

Fig. 4 Virtual prototype of sonic driller

3 MATHEMATICAL MODEL OF THE SONIC DRILLER

3.1. Modeling Drill Mobility

The sonic driller should be capable of climbing while avoiding overturn. Ignoring other possible disturbances, the sonic driller, only affected by its own weight and supporting slope, is regarded as a rigid body of fixed gravity mass with regard to stress analysis. The two tracks of the sonic driller, subject to various forces, are reacted by the ground force respectively. The sonic driller is likely to turn over on a slope when the vertical force between one side track and the ground approaches zero. So the necessary condition of turnover threshold should be:

$$P_2 = P_1 - \frac{2Mg \cdot (\cos\beta \cdot e + \sin\beta \cdot h)}{b} \geq 0 \tag{1}$$

The driller is driven by a dual-track system, composed of drive wheels, guide, suspension and track. Two conditions must be satisfied to ensure satisfactory mobility: enough output torque of hydraulic motor to drive the driving wheel, and greater adhesion friction stress between the ground and track than the soil resistance. When the sonic driller is climbing the slope, the force relationship is equation (2)

$$\begin{cases} F - f - Mg \cdot \sin\alpha = 0 \\ N - Mg \cdot \cos\alpha = 0 \\ N \cdot a + f \cdot h - F \cdot h = 0 \\ 2 \cdot \dfrac{\Delta p \cdot V}{2\pi} \geq F \cdot r \end{cases} \tag{2}$$

3.2. Model of the mast

There are two hydraulic cylinders to support the mast, shown in Fig. 5: one is to achieve the required angles usually perpendicular to the ground by turning the mast; the other is to improve the force equilibrium by placing the mast in a horizontal attitude. In order to raise the mast, the following momentum balance should be satisfied:

$$F_z \cdot \cos(\theta + \gamma - 90^o) \cdot L - m \cdot g \cdot \cos\theta \cdot L_z = 0 \tag{3}$$

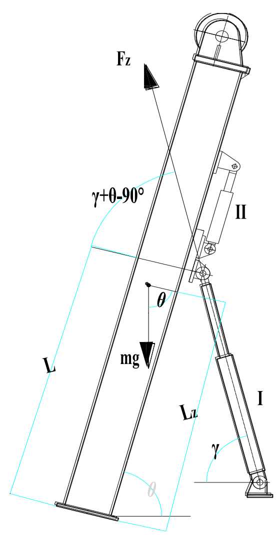

Fig. 5 Sketch of mast

3.3. Model of Sonic Top Driver

The sonic driller is a self-oscillatory system with energy derived from the hydraulic system, shown in Fig. 6. The excitation and propagation of the upper vibration energy in the string is absorbed by metal rubber isolators between the string and the hole as the string pierces the ground. The lower vibration energy is, however, necessary for drilling and sampling.

The isolator of the sonic top driver is manufactured as a metal rubber. It is assumed that the isolator is a coupled non-linear spring and damper. In order to achieve a satisfactorily precise linear model the vibration system should be linearized about some idea displacement point. The vibration equation can be expressed as formula (4). The non-linear spring stress and the non-linear damping force can be resolved by the Fourier series [16].

$$
\begin{cases} M\ddot{x}+c_e\dot{x}+k_e x = 2me(2\pi\dfrac{Q}{D_m})^2\sin 2\pi\dfrac{Q}{D_m}t=F_y \\ a_0=\dfrac{F_y}{M+m_0\cdot l} \end{cases} \tag{4}
$$

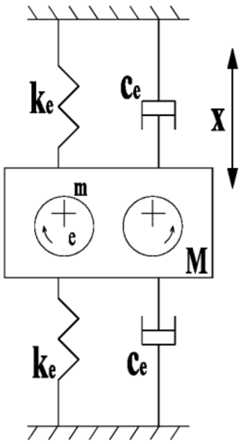

Fig. 6 Model of the vibration system

Table 2 Optimization Parameters

Item	Optimization value	Final value
walking motor discharge, ml/r	420	490
hydraulic cylinder diameter , mm	54.2	63
hydraulic cylinder diameter, mm	38.9	50
offset between gravity center and geometrical center, mm	0	123
vibration system mass, kg	50	90
single eccentric shaft mass, kg	2.8	2.8
shaft eccentricity, mm	22.5	22.5
single isolator stiffness, N/m	90000	95400

3.4. Optimizing Model Parameters

With most of the mechanical three-dimensional designs accomplished, some of the hydraulic and vibration parameters can be selected later, during model refinement. Depending on the mathematical model of the sonic driller, parameters of walking, climbing design, mast lifting design, vibration energy design and isolator design can be modified and optimized repeatedly. Some optimal results of key parameters can be generated according to the mathematical model. The national standards and manufacturing level are listed in table. 2.

4 SONIC DRILLER PROTOTYPE AND TESTING

The parts of the prototype, shown in Fig. 7, are manufactured in accordance with the optimization results of the virtual prototype technology. The assembly process was smooth and error free. Little difference is observed between the prototype and the virtual prototype. A series of experiments conducted to test the performances of sonic driller were also successful. The maximum walking speed and the maximum ground slope angle are 2.3km/h and 38^{o} respectively.

In order to test and verify the vibration capability and the vibration isolation effectiveness, as shown in Fig. 8, a set of four accelerometers were attached to the housings of the two counter-rotating unbalanced rotors and two others were attached to a part of the machine isolated from the drilling effect. Average acceleration value data was collected.

Fig. 7 photo of sonic driller prototype

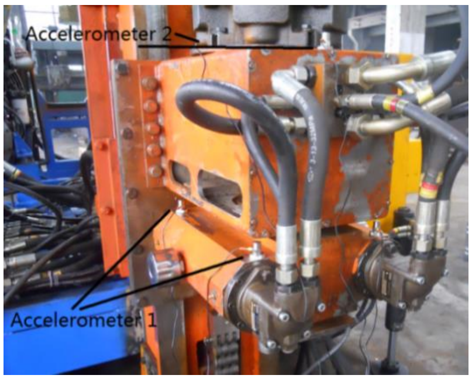

Fig. 8 Photo of vibration test

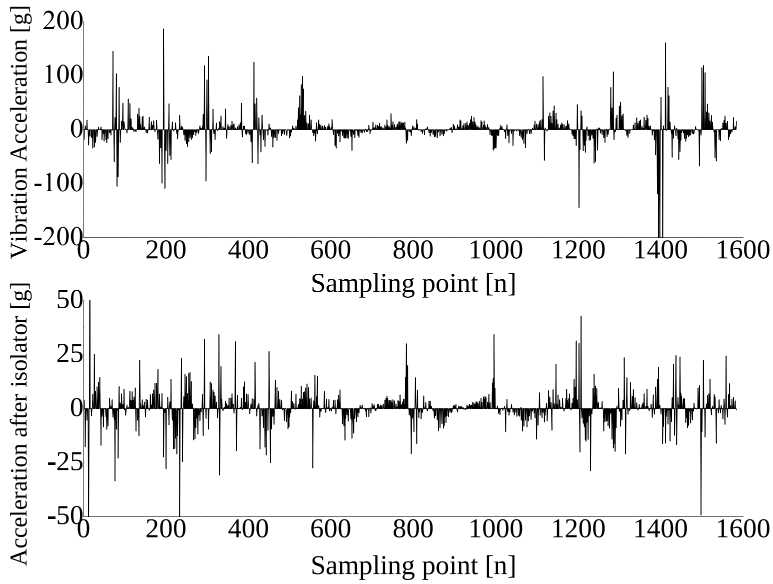

Fig. 9 curves of isolator effect

Fig. 9 shows the acceleration characteristics of the vibrating body and on an isolated region at a data sampling frequency of 3000Hz when the rotation speed of high speed hydraulic motor is 9000RPM, it is estimated that the maximum acceleration is about 150g (acceleration of gravity). While maximum acceleration in isolated regions is about 25g. During extended operation the isolators maintain stable temperature and function properly. This proved that the unconventional metal rubber isolator is satisfactory. The output vibration force is about 13.2kN according to the mass of vibration system and other parameters, which provides sufficient energy for drilling to the design depth of 40 meters.

On Nov. 4, 2011, the sonic driller prototype was drilling and sampling in sedimentary layer in Hebei province, P. R. China. The diameter of the drill pipe was 50 mm, and the diameter of the sampling bit was 108 mm. 23 test holes were drilled up to 47m in depth though multiple, alternating layers of clay, sand and gravel. The test was successful with a maximum core pull length of 3 meters.

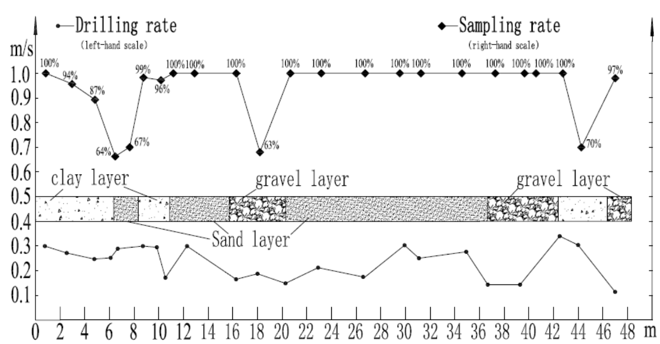

Fig. 10 Comparison of drilling rate and sampling rat

The sampling rate and drilling rate in different layers are shown in Fig. 10. The total core recovery reached over 90% and minimum single-trial core recovery was 63%. It proved that the sonic driller can drill and sample in gravel layer rapidly and smoothly if stone diameter is over 80mm. It is established that the sonic drilling rate is rapid with a maximum of rate 0.31 m/s. Sonic drilling provides high sampling efficiency, powerful drilling capability, no mud or water contamination during drilling and high-quality sample with integrity of geological information. It proved results show that the sonic drill design is satisfactory.

5. CONCLUSIONS

In the work, process visualization is set to testify the collision detection and optimize the overall layout. The mechanical design of commercially available sonic drills is simplified by including the novel isolator assembly and synchronization belt and omitting the usually required cooling system. The smarter prototype sonic driller is manufactured based on the virtual prototype, while the operating characteristics are studied and evaluated experimentally.

The core recovery can reach 90% by utilizing the novel sonic driller, not only with perfect coring quality, but with smooth and reliable operation. It indicates that the simplified scheme designed by virtual prototyping can be practically feasible, specialized in shortening the development cycle and improving the quality of products.

ACKNOWLEDGEMENTS

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