EXPERIMENTAL STUDY OF DUAL-RECIPROCATING-DRILLING MECHANISM USING DESIGN OF EXPERIMENT APPROACH

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ABSTRACT

Y. Gao et al. proved the feasibility of designing a wood-wasp (*Sirex Noctilio*) inspired drill for Earth and extra-terrestrial drilling and boring activities [1]. But before an optimised dual reciprocating drill design can be proposed, it is necessary to better understand the driving factors and the important parameters that influence this mechanism's performance and, power and force requirements. Indeed the insect's ovipositor is "optimised", through natural selection, for wood; but the dual reciprocating drill will bore into much different substrates. Here, the numerous parameters that could influence the studied mechanism's performance are identified and the test bench to experimentally evaluate there influence is described.

Key words: Wood-wasp; planetary drilling; biomimetics.

1. INTRODUCTION

Planetary drilling is called upon regularly. It is needed for producing samples for scientific payloads or sample return missions. The existence of the borehole also allows a robot or human to place captors in it for in-situ experimentation. Finally the data recorded during the drilling process itself gives access to the mechanical properties of the soil. However, the difficulty of drilling operations and the technical limitations of classical drilling techniques (high over-head force requirements) have limited the number of successful bore holes created on the surface of extraterrestrial bodies.

To propose an alternative to the classical rotary and percussive methods, Yang Gao et. al. proposed and studied a new drilling and sampling concept [1]. They were inspired by the working principle of the wood wasp (*Sirex Noctilio*) ovipositor: tubular structure capable of drilling into wood to lay the insect's eggs [4]. Thanks to a two-valve reciprocating motion, the insect's ovipositor is capable of generating additional force on its advancing valve by the reaction of the drilled substrate to the back-ward facing teeth of its receding valve (see Figure 1). Hereafter, any drilling mechanism inspired by this biological mechanism will be referred to as DRD (Dual-Reciprocating Drill/Drilling). A simple DRD mechanism was tested on three different drilled substrates (condensed chalk, non fired clay and lime mortar) at 9 different power levels [1]. Their DRD mechanism drilled faster in softer substrates (lower compressive strength) than in harder ones. Authors highlighted the fact that drilling speed generally grew with penetration depth. They also proposed an empirical model allowing to predict the penetration speed of their DRD mechanism based on input power and substrate compressive strength. But above all the experimental work presented in [1] was the first implementation of DRD and proved the feasibility of DRD in soil and low strength rocks. However their model did not include the geometry of the valves and other interesting parameters. The experimental work presented here should allow the elaboration of a more complete model.

The large diversity of wood wasp ovipositor structures [3] and the study of their working principle [4] have fostered two ideas. The main one is the use of the reaction of the drilled substrate to the receding valve's backward facing teeth. The force generated by the backward facing teeth can be used to increase the available force for the progressing valve (see Figure 1). In a low gravity environment this will be very useful. The other idea is the direct transmission of the force generated by the backward-facing teeth to the progressing valve (though the wood wasp ovipositor is not thought to do so). By directly transmitting the force to the progressing valve, the drill stem or ovipositor does not have to transmit this extra force and faces less buckling issues. Figure 1 presents two implementations of DRD: on the left the force generated by the backward facing teeth is transmitted via the drill stem; on the right, the second idea is implemented.

Implementing these two ideas to propose a novel planetary drilling system intuitively seems to be the best path to follow. However it is important to recall that the wood wasp drilling mechanism is "optimised" (through natural selection) for a fibrous material (wood) that has numerous micro-structures (wood cells). Vincent et. al. in-

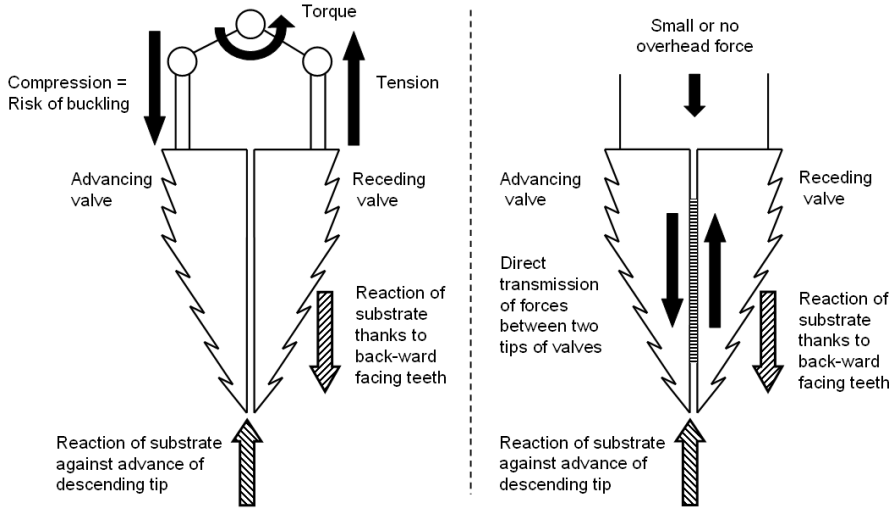

Figure 1. Implementation of dual-reciprocating drilling. Without direct transmission of force the valves slide on one another (left). The direct transmission of force between the two valves (right) can be done by ramping piezo-electrics for example. In both cases the drill stem above the valves is not represented to scale and would be much longer.

ferred that the size of the teeth on the wood wasp ovipositor are proportioned to be compatible with the size of the wood cell walls [4]. What does this optimal tooth size become when the substrate drilled into is no-longer wood but regolith or soft rocks? Another more practical issue, but of very high importance, is the technological implementation of the DRD mechanism. Even if the concept proposed Figure 1 right is shown to have the best performance, a technological solution must be found to build it. This can not be done yet, since there is no tool to predict the forces necessary for such a mechanism.

Here, the efforts and the experimental work done to resolve these issues are described. First the numerous parameters that could have an influence on the performance of a planetary DRD are identified. To evaluate the influence of some of these parameters on DRD efficiency and to characterize the forces and power requirements of DRD, a test bench was designed, built and tested. The large number of parameters present has pushed authors to propose a classical design of experiment technique to identify the significant or driving parameter of DRD performance.

2. IDENTIFIED PARAMETERS

12 parameters have been identified (nine geometric ones and three operational ones, see Table 1. The drilled substrate characterisation is under discussion.

2.1. Geometric parameters

The morphology of the wood wasp ovipositor is highly complex. Here we propose to mimic it in a simplified manner. The general form of the DRD valves will be a cone on top of a cylinder. The general form can be fully defined with three parameters: cone apex angle α, cylinder length L and cylinder radius R. We have chosen to design two general types of teeth: one for the conical part and one for the cylindrical part. To fully define tooth geometry, the number of teeth on each part must be known (N_1 and N_2) as well as two angles for each teeth type (α_1, γ_1 and α_2, γ_2). This gives us a total of nine geometrical parameters (see Figure 2).

Table 1. Intended values or range of parameters to be tested.

	Values		Units		Values		Units
R	10	5	mm	L	70	40	mm
α	15	30	deg	d	0	2	m
α_1	25	40	deg	γ_1	65	80	deg
α_2	20	40	deg	γ_2	30	50	deg
N_1	3	5		N_2	10	15	
f	0	240	Hz	δ	0	15	mm

2.2. Operational parameters

Once the geometry of the DRD mandible has been defined, the manner it is reciprocated must be defined. The amplitude of the movement δ will most probably influence drilling performance. The speed at which the reciprocating cycle is done or the frequency f of the cycle must also be defined. These two parameters have been

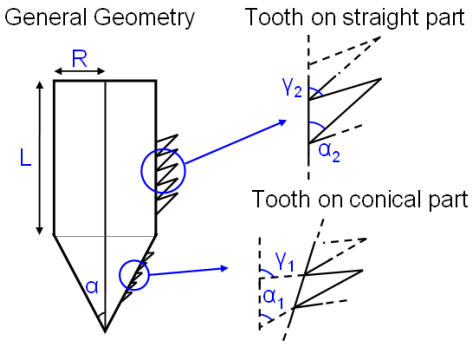

Figure 2. Schematic of the parameters defining valve geometry.

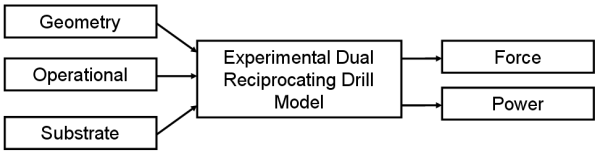

Figure 3. Expected output of test bench experimentation.

chosen as the two operational parameters. Other parameters that are linked to these two could have been chosen: the input electrical power, the drilling speed, etc. The other operational parameter of high importance is the depth d of the DRD valves.

2.3. Substrate parameters

In order to asses precisely the potential of DRD technology, we wish to explore a large diversity of substrates: loosely compacted sands, highly compacted regolith simulants and also low unconfined strength rocks like the ones used in [1]. It is thus very difficult to define a set of parameters that can define the mechanical properties of rocks and granular materials alike. When applicable, internal angle of friction, cohesion and strength parameters will be used.

3. DUAL RECIPROCATING DRILL TEST BENCH

3.1. Expected output and design requirements

Once these parameters have been identified, it is necessary to link them to the DRD power and force requirements. An experimental test bench was thus designed to be able to experimentally elaborate tools allowing the prediction of force and power requirements. Figure 3 is an illustration of the expected outcome of the experimental work.

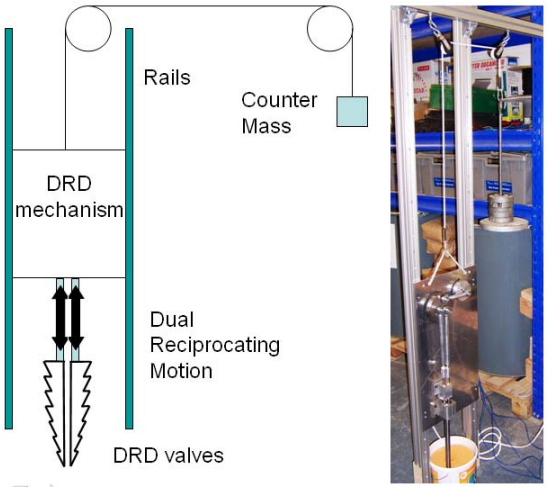

Figure 4. Schematic and picture of manufactured test bench for dual-reciprocating drilling. The valves in the schematic are represented seperatly only for lissiblity.

Apart from allowing the exploration of the influence of all the parameters identified here above, the test bench must allow to control the overhead force that is applied to the DRD valves. Indeed the major foreseen advantage of a space DRD is its capability of creating a borehole with very low or no needs of overhead thrust. The test bench has thus been designed and built to answer these two requirements (test parameters and control over-head thrust).

3.2. Description of Test Bench

Figure 4 presents the general concept of the test bench and a picture of it. A plate supporting the DRD mechanism is attached to two rails allowing its vertical translation. A counter mass is attached to the plate in order to control the over-head thrust applied to the DRD valves. On the DRD plate, a mechanism transforms the rotation of a continuous current electrical motor into a dual reciprocating motion. At the end of this mechanism, the DRD valves are attached. Thus as the DRD valves penetrate the drilled substrate, the entire plate supporting the DRD mechanism and motor advances. This implementation of DRD has the advantage of simplicity since a deployment mechanism between the actuator or motor and the DRD valves is not necessary.

The mechanism that allows the transformation of the motor's rotation into a dual reciprocating motion has been designed to allow amplitude modification of the dual reciprocating motion δ without highly modifying the symmetry of the cycle. The DRD valves are composed of the drill heads (which are defined by the geometrical parameters described here above) and of a linear guiding system which constrain the two valves to stay together and slide one on each other during drilling. An example of valve positions versus motor angle is given in Figure 5.

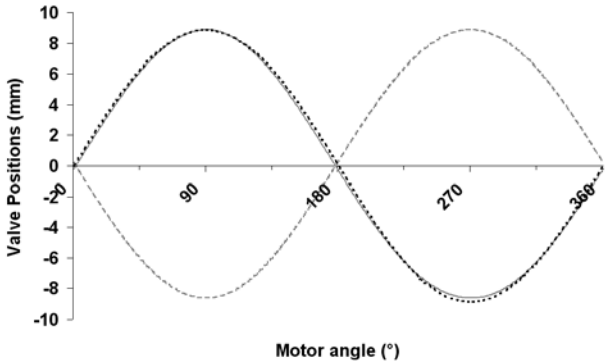

Figure 5. Possible evolution of valve positions versus motor angle. The solid line represents one valve and the black dotted line near it is a pure sinus used as reference. The grey dotted line is the other valve.

The continuous current motor is controlled through its input tension. A voltmeter allows a control of the imposed tension and a current meter measures the intensity in the motor. The drill progression is measured by a fixed ruler system on the plate and rails. The mechanism frequency is also recorded.

3.3. Mimicing low-gravity environments

The counter mass does not allow mimicking zero or low-gravity environments. The counter-mass only allows the control of the vertical thrust applied to the DRD valves, which is in part linked to the local gravity. On the Moon, Mars or beyond, the DRD torque is countered by the differential reaction of the ground, which is proportional to the local gravity. On Earth in the DRD test bench, this torque is countered by the rails, which are not affected by the presence of a counter mass. The counter-mass thus allows to control the over-head thrust on the DRD valves but it does not allow to mimic a low gravity environment. Moreover the effect of gravity on the drilled substrate behaviour and drillings evacuation can not be controlled and simulated with the present test bench.

3.4. Test Bench Evaluation

Before doing an extensive test campaign, the DRD test bench was evaluated. The solid friction in the rails and counter mass system and the system's inertia make the system stable for an interval of counter mass values. This must be taken into account to when calculating the over-head force. The actuation system also presents some friction. This friction is evaluated by making the actuation system run without drilling into substrate. It would be interesting to measure this friction with different contact pressure between the two valves, since this pressure will vary as the substrate applies a higher pressure on the two valves with increasing depth.

4. DESIGN OF EXPERIMENT

A complete factorial experiment plan would be much too important to carry out. Indeed, even if only two levels of each operational and geometric parameter are chosen, this would induce 2^{11} experiments to do for each tested substrate. Only the main effects and maybe the two-factor interactions are of interest since the three or more factor effects will probably be very minimal and lost in the high dispersion inherent to drilling tests (due to substrate heterogeneity). Thus a fractional-factorial design of experiment will be used to plan and analyse the experimental work [2].

5. CONCLUSION

Observations of the working principle and physiology of the wood wasp's ovipositor have fostered two ideas for the implementation of dual-reciprocating drilling. Due to the different nature of the drilled substrates (wood for the insect; soil, regolith and rocks for the man built DRD), the geometrical and operational parameters of the DRD must be adapted to the new substrates. To allow this optimisation, a test bench was designed to test DRD in different conditions while controlling the over-head force applied on the valves. By using a rigorous design of experiment approach, this test bench should allow the experimental determination of laws linking the geometric and operational parameters and the substrate properties, to DRD performance and, to energy and force requirements. It could also allow further experimentation such as a study of the influence of positive and negative over-head forces or, of an asymmetrical cycle on DRD performance.

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