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An ultrasonic compactor for oil and gas exploration

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Abstract

The Badger Explorer is a rig-less oil and gas exploration tool which drills into the subsea environment to collect geological data. Drill spoil is transported from the front end of the system to the rear, where the material is compacted. Motivated by the need to develop a highly efficient compaction system, an ultrasonic compactor for application with granular geological materials encountered in subsea environments is designed and fabricated as part of this study. The finite element method is used to design a compactor configuration suitable for subsea exploration, consisting of a vibrating ultrasonic horn called a resonant compactor head, which operates in a longitudinal mode at 20 kHz, driven by a Langevin piezoelectric transducer. A simplified version of the compactor is also designed, due to its ease of incorporating in a lab-based experimental rig, in order to demonstrate enhanced compaction using ultrasonics. Numerical analysis of this simplified compactor system is supported with experimental characterisation using laser Doppler vibrometry. Compaction testing is then conducted on granular geological material, showing that compaction can be enhanced through the use of an ultrasonic compactor.

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Keywords: Ultrasonic compactor; geological materials; densification

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1. Introduction

The compaction of granular materials has been investigated for many years. For example, the consolidation of granular materials has been essential in dental filling fabrication, plastic moulding, and pharmaceutical tableting

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(Matsuoka (1994), Levina et al. (2000), Deitch et al. (2002), Fini et al. (2009)). Improvements to the compaction processes have largely been sought to either promote enhanced particle bonding or fusion, or to create products from granular materials with high strength, such as paracetamol or ibuprofen. More recently, ultrasonics has been adopted as a method of further improving the compaction process. It has been demonstrated that ultrasonic vibrations have the capacity to improve the strength of particulate samples through further enhancement of particle bonding. Reduced compaction forces have also been attributed to the ultrasonic vibrations (Levina et al. (2000)). In order to improve the compaction performance, where an increase in the densification of the granular materials is desired, it is important in the design of the compaction system that the interaction with the granular materials is considered. For ultrasonic compaction, the use of a resonant compactor head (RCH) is necessary. In this investigation, an optimised resonant compactor head (RCH_O) has been designed using the finite element analysis (FEA) software Abaqus/CAE v.6.13, where the RCH_O is designed to vibrate in the longitudinal mode of vibration at 20 kHz. Improvements to the compaction process for quartz sand using ultrasonics is also demonstrated, using a simplified version of a resonant compactor head (RCH_S), so that it can easily be incorporated into a lab-based test environment. This simplified compactor head has not been specifically optimised for enhancing compaction of granular material, unlike the optimised compactor head. The RCH_S is driven by a Langevin piezoelectric ultrasonic transducer (Sonic Systems L500), incorporates a flange to enable it to be secured into a housing cage, and is configured so that it can fit easily into a mechanical testing machine (Zwick Roell Z250).

1.1. The Badger Explorer subsea exploration tool

The Badger Explorer is a novel oil and gas exploration tool which propagates through the subsea environment, thereby creating drill spoil which must be efficiently compacted. Consequently, a greater understanding of the compaction of granular geological materials must be achieved. For example, the compaction of a geological material such as sand, which comprises a wide range of chemical compositions and grain particle sizes, is known to be complex (Proud et al. (2007)). A more detailed understanding is required of the influence of the physical characteristics of granular material particles on the capability of ultrasonic vibrations to improve compaction, particularly for geological materials encountered in oil and gas exploration. In the Badger Explorer technology, the drill spoil will be compacted behind the tool to generate a highly densified plug. To evaluate the challenges which face this technology, an ultrasonic compactor is designed which can be used in experiments to mimic the system which will be employed in the subsea environment.

1.2. Effect of ultrasonics on the compaction process

Ultrasonic compaction has been used with success in a wide variety of applications but, despite this, a better understanding of the particle interactions under the influence of ultrasonics is required, in addition to how the ultrasonic compactor can be designed and optimised to enable an efficient compaction of different granular materials. However, there are distinct known advantages to compaction using ultrasonics. For example, it has been argued that in the production of plastic moulds, a far higher precision of manufacture is achievable through the use of ultrasonic compaction of the polymeric powder used to generate the moulds (Matsuoka (1994)). This is because the required temperatures in the fabrication process are lower for the process involving ultrasonics than for conventional moulding. The production speed of composite materials has been shown to be increased by the application of ultrasonic compaction in the manufacturing process (Justo et al. (2015)). In tabletting production for the pharmaceutical industry, many advantages have been identified of ultrasonic compaction (Levina et al. (2000)), including improvements in the density of the tablet, and the uniformity of the granular material compacted to form the tablet. In addition to lower compaction forces under the application of ultrasonics, a much larger crushing strength of tablets has also been identified. This means that the final compacted sample exhibits a significantly higher strength.

Due to the widely reported benefits that ultrasonic vibrations can impart on a compaction process, an ultrasonic compactor system has been developed, which would find application in the Badger Explorer subsea exploration technology. An optimised compactor is also shown, to demonstrate some of the design challenges. This research enables the further understanding of the effectiveness of the ultrasonic compaction of granular geological materials.

2. Design of the ultrasonic compactor system

The complete ultrasonic compactor system configuration which was designed and fabricated for this study is shown in Fig. 1, and consists of three primary components, comprising an ultrasonic transducer with RCH connected, and a housing cage.

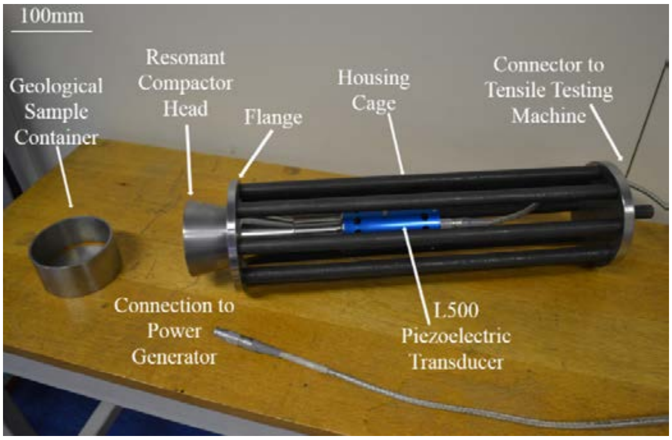
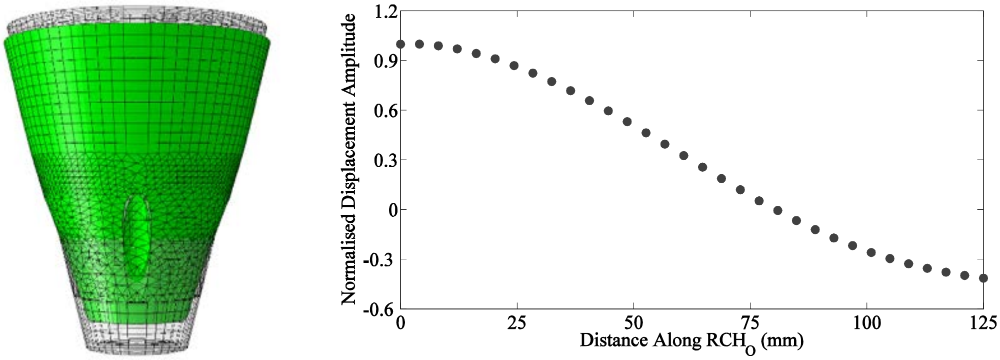


Fig. 1. The ultrasonic compactor system configuration, in this case showing the RCH_S.

2.1. An optimised resonant ultrasonic compactor head

The Badger Explorer subsea exploration tool contributed a number of key design constraints. The tool necessitates a compactor which operates at 20 kHz in the first longitudinal mode of vibration. An input face diameter of 40 mm and an output face diameter of approximately 100 mm are required and this means there is potential for significant loss in amplitude of the horn between the input and output faces, with a resulting amplitude gain of less than one. A criterion to reach a value of gain as close to one as possible became an important design consideration. Channels are required to be incorporated into the compactor head to permit the transport of spoil material through the system. Finally, the output face is required to have a load bearing capacity of 10 tonnes. The initial design iteration of the RCH_O is shown in Fig. 2(a).



(a) (b)

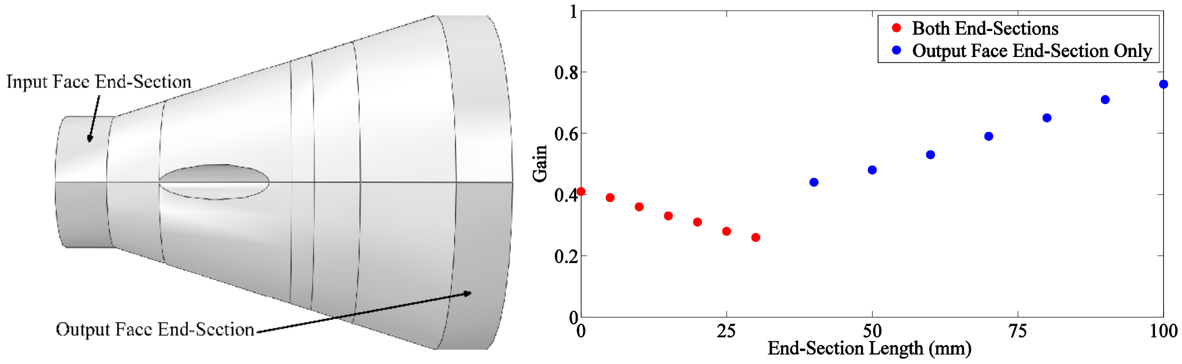
Fig. 2. The first iteration of the RCH_O, showing (a) the design configuration in the longitudinal mode at 19.92 kHz, and (b) the normalised displacement amplitude as a function of the distance along the RCH_O length. Displacement amplitudes can be displayed in terms of microns, but have been normalised for this analysis.

The compactor head is made from grade 5 titanium, due to its high strength and good acoustic performance. In the FEA model, the material properties of Ti-6Al-4V were designated as $\rho = 4430$ kg/m^3, $\nu = 0.33$, and $E = 110$ GPa. The

RCH designs have short cylindrical end-sections of uniform diameter at the input and output faces to allow the resonant frequency to be further tuned post-fabrication if necessary by small amounts of material removal.

In the design process, three parameters were monitored through iterative changes to the FEA models, the resonant frequency, modal frequency separation, and the gain. Modal frequency separation is important to prevent coupling of different modes of vibration. Ideally, a modal frequency separation exceeding 1 kHz is required. Based on the initial design specifications, a configuration was produced in FEA which resulted in the longitudinal mode frequency being predicted at 19.92 kHz, (Fig. 2(a)), and the gain could be extracted from the longitudinal displacement plotted along the axis of the compactor head, (Fig. 2(b)).

The predicted value of gain from the FE model was much lower than one in Fig. 2(b), being approximately 0.42, because the output face of the compactor head is much larger in diameter than the input face. Furthermore, the calculated modal frequency separation was poor, with a mode predicted at 19.36 kHz exhibiting flexure of the output face, and a bending mode at 21.00 kHz. The design of the RCH_{O} was therefore evolved using two methods, both of which aimed to improve the gain value. Uniform-diameter end-sections were introduced at both the input and output ends of the compactor head, and slots were incorporated around the circumference. During this optimisation process, the total length of the RCH was adjusted to maintain resonance at 20 kHz. The results in Fig. 3 show the effect of varying the end-section lengths, shown in Fig. 3(a). The results in Fig. 3(b) show the influence on gain of modifying the length of the end-sections by equal amounts, and only altering the length of the output face end-section.

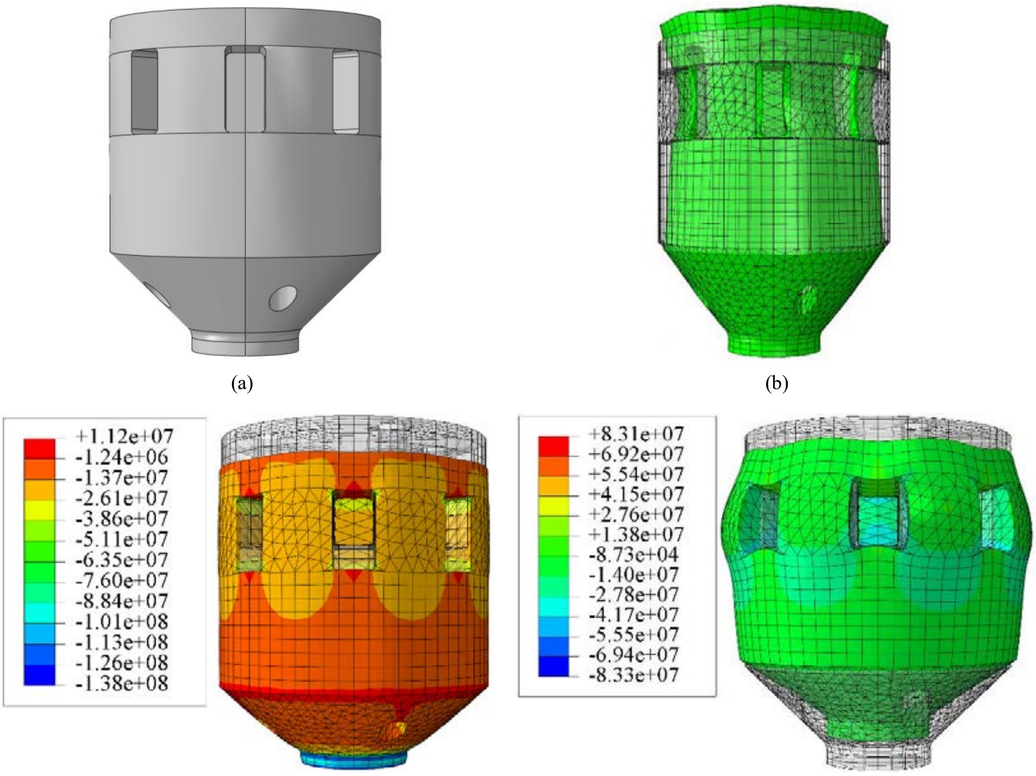


(a) (b)

Fig. 3. Evolution of the design, showing (a) the end-section locations, and (b) the effect of input and output end-section length on gain, and the influence of output end-section length variation only.

It is evident that by increasing the length of both end-sections, the value of gain is worse, reducing to almost 0.2. However, by increasing the length of the end-section at the output face, the gain value moves close to one. Based on the results shown in Fig. 3, and through the inclusion of slots in the configuration to further improve the gain, a final design solution was developed. Shown in Fig. 4 are the RCH_{O}, the calculated longitudinal mode at 19.69 kHz, and the stress distribution. For the stress analysis, two simulations were performed. The first incorporated a static pressure loading of 10 tonnes applied to the output face of the RCH_{O}, with a fixed boundary condition defined at the input face, and the results are shown in Fig. 4(c). The second was a dynamic stress analysis in the longitudinal mode of vibration, for a simulated input displacement amplitude of 10 µm, the results of which are displayed in Fig. 4(d).

The fatigue limit of grade 5 titanium is around 500 MPa in air (Hosseini (2012)). The FEA results hence show that the RCH_{O} will be able to tolerate a pressure of 10 tonnes during operation. A bending mode was calculated to exist at 1430 Hz lower than the longitudinal mode frequency, and another 1295 Hz higher, indicating an acceptable modal frequency separation. The gain value was calculated to be 0.98, which is very close to 1.0 and demonstrates that the design satisfies the aim of resulting in as small a loss in amplitude as possible between the input and output faces of the compactor head.



(a) (b)

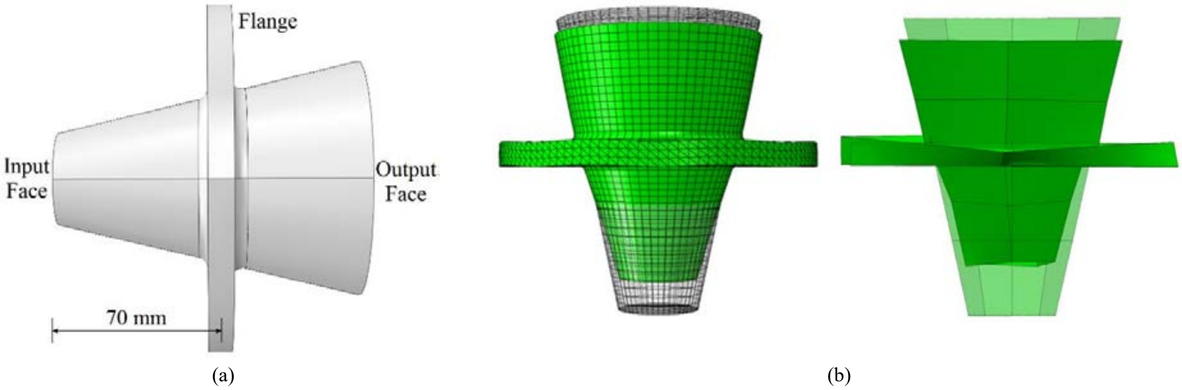
(c) (d)

Fig. 4. The final design solution from FEA, showing (a) the $\mathrm{RCH_O}$ configuration, (b) the longitudinal mode at 19.69 kHz, (c) static stress distribution in the longitudinal direction for a pressure loading of 10 tonnes, in Pascals, and (d) the dynamic stress distribution for an input displacement amplitude of 10 μm at 19.69 kHz in the longitudinal direction, in Pascals.

2.2. Analysis of the simplified resonant ultrasonic compactor head

The $\mathrm{RCH_S}$ designed for the compaction experiments was tuned to the piezoelectric transducer longitudinal mode frequency of 20 kHz. The $\mathrm{RCH_S}$ had to be strong enough to withstand the compaction forces in the test set-up, up to approximately 8 kN for the experiments conducted as part of this research. The $\mathrm{RCH_S}$ was fabricated from structural steel (S355J2), and is shown in Fig. 5(a). Additionally, a flange was incorporated on the $\mathrm{RCH_S}$ to enable the connection of the housing cage. To ensure the flange does not fail during operation of the compactor system and does not affect the longitudinal-mode vibration behaviour of the compactor, it was located as close as possible to the nodal plane of the $\mathrm{RCH_S}$.

The longitudinal mode of vibration was calculated using FEA, and the resonant frequency was predicted to be 19.89 kHz. This result is shown in Fig. 5(b), where the deformed mode shape is shown in green. Only a slight motion of the flange was predicted, which must be sufficiently small to avoid high stresses during operation when affixed within the complete compactor system. To validate the FEA predictions, experimental modal analysis (EMA) was used to measure the modal response of the $\mathrm{RCH_S}$. The EMA set-up comprises a 3-D laser Doppler vibrometer (Polytec CLV) connected to a power generator and signal analyzer system. Frequency response functions are measured at discrete points on the vibrating structure using acquisition software (SignalCalc), after which the data is processed (ME'ScopeVES). The EMA of the $\mathrm{RCH_S}$ estimated the longitudinal mode of vibration at a frequency of 19.58 kHz. The result of this measurement is shown in Fig. 5(b), where the deformed shape is shown in dark green.



(a) (b)

Fig. 5. Analysis of the RCHs, showing (a) the configuration, and (b) the longitudinal mode at 19.89 kHz from FEA (left), and 19.58 kHz from EMA (right).

A very close correlation has been achieved between the resonant frequency and associated mode shape of the RCHs from the FEA and EMA. This is a difference of 1.16% in the measured and calculated frequency, demonstrating the reliability of FEA in the design of the RCHs.

3. Compaction performance

The ultrasonic compactor system incorporating the RCHS was tested on samples of granular quartz sand. Each sample consisted of quartz sand deposited into a cylindrical container of 50 mm depth, and an inner diameter of 107 mm, which permits a small circumferential clearance of the RCH. In each test, the quartz sand was deposited through a funnel from a height of 480 mm above the container, to ensure consistency and uniformity in the test samples. In the compaction test, the compactor was driven at a speed of 8 mm/min by the mechanical testing machine, and was excited by the ultrasonic generator/transducer at two different ultrasonic amplitudes, 0.80 μm and 1.60 μm at the output face of the RCHS. The experiment was also carried out for compaction with no ultrasonic excitation of the RCHS. The force-distance relationships are shown in Fig. 6, for up to 8 kN of measured force. The results represent the average of three compaction tests, with a new sample prepared for each test. A force limit was set in the experiments in order to protect the RCHS during operation.

The results show that the compaction distance achieved, up to the 8 kN force limit, is much higher for ultrasonic compaction, even for the very small ultrasonic amplitudes considered in this study. The ultrasonic vibrations generate a fluidised motion of the sample particles, which is exhibited as a reduction in resistance to the motion of the compactor into the sample. Furthermore, the particles occupy an increased number of void spaces, improving densification under ultrasonic compaction.

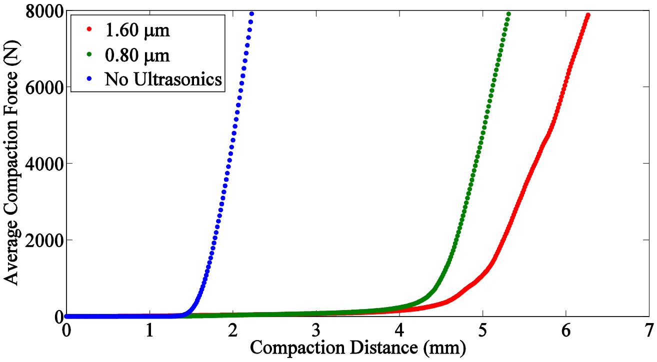


Fig. 6. Compaction force-distance relationship for tests at different ultrasonic amplitudes.

The quartz sand samples comprise particles of different sizes and chemical compositions. Particle size, size distribution and particle composition are all known to influence compaction and can be expected to influence ultrasonic compaction. Further investigations are required to relate these characteristics of the sample geological materials to their ultrasonic compaction. This is also required in order to further improve the ultrasonic compactor design to achieve higher densification at lower compaction force.

4. Conclusions

This study has presented the design of a resonant compactor head for ultrasonic compaction of granular geological materials in oil and gas exploration, using FEA. It was shown that a compactor head can be designed with a gain of close to 1.0 for a compactor where the output face diameter is much larger than the input face dimeter. This was achieved using FEA, principally by modifying the length of a uniform cylindrical end-section, and by including slots in the configuration. Throughout the design iterations using FEA, the resonant frequency was maintained at 20 kHz and modal frequency separation met the design criterion.

A simplified version of the resonant compactor head was fabricated to be incorporated as part of a complete ultrasonic compactor system driven by a Langevin piezoelectric transducer and mounted in a mechanical test machine. Using this ultrasonic compactor, the enhanced compaction of granular quartz sand was demonstrated, compared to compaction without ultrasonics. It is anticipated that further optimisation of the ultrasonic compactor will result in improvements in the compaction process, to create compacted samples with increased density and strength.

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