Numerical analysis and noise detection for design optimisation of an ultrasonic transducer

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Abstract. The characteristics of a Langevin transducer are studied using a combination of numerical and experimental techniques, which reveal the effect of minor design changes on its performance. The experiments were performed using a microphone and voice-recording software capable of measuring frequencies up to 41 kHz; the obtained signal was analysed in MATLAB. A three-dimensional finite element model of the analysed transducer was also developed in a commercial finite element software ABAQUS/Standard and used for numerical simulations of its response to different excitation conditions. The transducer system was optimised using the results of noise detection and FEA.

1. Introduction

Langevin transducers are widely used in high-power ultrasonics for applications ranging from cleaning to advanced machining and cutting of intractable materials [1-3]. In ultrasonically assisted machining, piezoelectric ceramic discs are used to excite the horn. Different types of cutting tools are attached to the horns; the tool attachment to the horn is achieved by means of screws, bolts or by other assembly procedures. In ultrasonically assisted drilling (UAD) studied here the drill bits can be attached to the transducer in different ways. Several authors presented the setup for conducting the ultrasonic machining detailed [4-7] but in certain studies the information about the setup, especially the tool holding procedure to the transducer, is kept confidential [8-10].

The studies revealed that the attachment of a tool to the horn plays a critical role in vibration modes; also the resonance frequency changes by changing the position of the free length of the tool with respect to the tool attachment [11]. When the transducer is excited the system produces sound/noise. The variation sound emanating by the system can be used as an indication of changes in the system. But such variations cannot be differentiated solely with human audibility.

Techniques such as acoustic emission and vibration measurement systems are used in the industry for different condition monitoring purposes e.g. for valve leak detection, bearing maintenance and detecting fluid flow through pipes [12-14]. In such applications the noise and vibration data is collected, then compared against the standard values and faults are monitored. Once the errors are detected, maintenance of the system is carried out often by replacing or repairing the individual parts of the assembly.
Finite element method (FE method) is broadly used by the engineering community in various tasks, from design and development to manufacturing and optimisation. Design of ultrasonic transducer with the aid of FE approaches are typically used to determine the vibration modes and amplitude, voltage required for piezoelectric ceramic materials and natural frequency of the systems [11, 15-16]. But optimisation of the ultrasonic transducers, especially used for UAD, has not been based on a combination of noise detection and FEA analysis.

Here, we study a behaviour of different waveguides for a horn as well as an attachment-systems for drill bit, connected to the ultrasonic transducer. The noise, beyond the audible range, emanated by the systems was recorded using a microphone and processed in Matlab™. The difference in the ultrasonic signal, recorded in the frequency range between 20-41 kHz, was analysed by this technique. A pre-validated FEA model was used for further analysis of each part of the attachment system, assessment of errors and optimisation of the transducer system.

2. Problem formulation

Ultrasound transducers used for drilling are mostly manufactured for a single drill bit i.e. for each drill bit a special transducer was designed [4-7]. A special adapter which consists of a collet chuck for drill bits of different size was designed and manufactured so that the same pre-manufactured transducer can be used with different bits. The adapter was attached to the pre-manufactured transducer providing a capability to compensate the different size of drill bits with the help of collet-chucks of different sizes (Figure 1).

Figure 1. Transducer, adapter and collet-chuck for rapid tool change

Initial drilling experiments were conducted on carbon fibre reinforced plastic using the transducer assembly shown in Figure 1. However, with an increase in drilling depth the thrust force reduction in UAD was completely lost. It was around 50% in the beginning of complete drill bit engagement with the workpiece but the ultrasonic effect depleted completely through the half depth. The respective evolution of thrust force is presented in Figure 2.

Figure 2. Thrust force evolution: ultrasonic effect depletion
2.1. Noise detection

To elucidate the cause for ultrasonic effect-depletion, free-vibration tests were conducted on the transducer with the whole transducer assembly vibrating at the resonance frequency and produced sound being recorded. To achieve this, the microphone was placed near the ultrasonic-transducer system and noise/sound was recorded for 15 seconds. The acquired signal was processed using Matlab™; the obtained results are presented in Figure 3. The signals showed that the sound was not continuous, demonstrating that some of the transducer parts were not vibrating in harmony with the system. At that stage it was understood that the whole assembly should be analysed and finite element analysis was carried out to achieve this.

2.2. Finite element analysis

A pre-validated 3-D model was developed in FEA software Abaqus/Standard and used to analysis the complete assembly. In the FEA model the Linear Perturbation Analysis was carried out for eigen-values, vibration modes and natural frequency analysis using the AMS solver. In our free-vibration experiments, the transducer vibrated at frequency of 24.6 kHz whereas in the simulation the same mode was observed at 23.6 kHz. The analysis revealed that under vibration the collet-chuck was getting dis-engaged with the adapter-assembly (Figure 4). This was considered to be the primary cause of loss of ultrasonic effects during drilling.

**Figure 3.** Sound evolution for transducer vibrating at resonance frequency (a) For 15 Sec (b) For 6 Sec (c) For 0.0001 Sec from 3.6102 to 3.6103 Sec

**Figure 4.** FEA of transducer system (resonance vibration – longitudinal mode) (a) Complete transducer system (b) In compression (c) In expansion
3. New adapter and grip screws

To solve the problem a new conical adapter was analysed using the developed FE model. The adapter holds the drill bit with the help of grip-screws. The FEA analysis revealed that the new system was more reliable compared to the collet-chuck system. After manufacturing free vibration tests were carried out. The experimental value of resonance was observed at 25.5 kHz whereas the FEA resonance value was found at 24.9 kHz. The longitudinal vibration mode is shown in Figure 6 (a) and the manufactured system in Figure 6 (b).

The sound test was carried out and a smooth sound signal was measured for the new design (see Figure 7). This conical adapter system also allows the use the same transducer for different sizes of the drill bits efficiently.
4. Drilling experiments

The drilling experiments were conducted using new transducer system and consistent results were observed. The system resonance frequency was found as 25.5 kHz with the vibration amplitude of 12 µm (peak to peak). The experiments were conducted on the same drilling parameters and same workpiece. The thrust force trace is presented in Figure 8.

Conclusions

The following conclusions were achieved based on the undertaken study:

- A combination of experimental and numerical studies allowed to design a new transducer
- A combined approach for design optimisation of ultrasonic transducer was developed
- A successful series of drilling experiments revealed the suitability of optimised transducer system for drilling
- The noise detection allows to elucidate the design shortcomings as well as optimises the ultrasonic transducer
- The developed FEA model is an effective tool in designing and optimisation of the transducer

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