Simulation-Driven Design of Ultrasonic Horns for Precision Micro-Grinding Applications

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Abstract— **High-precision micro-machining and grinding processes are increasingly vital for the fabrication of next-generation components in aerospace, biomedical, and semiconductor industries. As the demand for tighter tolerances, superior surface finish, and material integrity increases, conventional machining techniques face limitations in tool wear, heat generation, and material removal efficiency. Ultrasonic Vibration-Assisted Grinding (UVAG) and Ultrasonic Minimum Quantity Lubrication (UMQL) have emerged as promising solutions, enabling improved performance through high-frequency vibrations superimposed on conventional grinding operations. This research focuses on the simulation-based design and optimization of ultrasonic horns, critical components in delivering high-frequency energy, to enhance micro-grinding effectiveness. Traditional horn designs often rely on heuristic and trial-and-error methods, which are time-consuming and prone to detuning, especially in precision applications. To address this, we propose a comprehensive design framework integrating analytical modeling, finite element simulations, and experimental validation. Initial design begins with resonance length estimation using elastic wave propagation theory, followed by the development of parametric CAD models. Modal and harmonic analyses in ANSYS Workbench ensure tuning accuracy to the target frequency (20 kHz), maximize amplitude gain, and minimize stress concentrations. A coupled horn-workpiece model is simulated to replicate realistic operational conditions. Post-simulation, horns are fabricated using ultra-precision machining, and their vibrational characteristics are validated with frequency analysers and displacement measurement systems. Deviations from the simulated behavior are corrected via iterative refinement, ensuring system compatibility and robust performance. This study presents a robust and adaptable methodology for the design of ultrasonic horns specifically tailored to micro-machining and precision grinding applications. The approach significantly advances ultrasonic tool development by offering improved dimensional accuracy, streamlined design processes, and increased operational efficiency. Moreover, the methodology is well-aligned with Industry 4.0 principles, enabling seamless integration into digitally connected, data-driven manufacturing ecosystems.**

Keywords- Ultrasonic horn; UMQL; UVAG;, Precision Grinding

I. INTRODUCTION

Precision micro-grinding of advanced materials is highly challenging due to the generation of high cutting forces, rapid tool wear, and poor surface quality [1]. To address these limitations, application of ultrasonic vibration has emerged as a powerful technique to improve the performance of precision machining processes, particularly in the micro-grinding of hard and brittle materials such as ceramics, aerospace alloys, and advanced composites. Conventional grinding at the microscale often suffers from excessive heat generation and limited surface integrity, but by superimposing high-frequency vibrations onto the tool or workpiece, ultrasonic vibration-assisted grinding (UVAG) significantly reduces cutting forces, enhances chip removal, lowers temperatures, and improves surface finish and tool life [2]. These advantages make UVAG an attractive solution for advanced manufacturing applications. However, at the core of any ultrasonic machining system lies the horn, a resonant component that transmits and amplifies vibrations from a piezoelectric transducer to the cutting zone. Special attention is required for designing and manufacturing the horn correctly, which may otherwise hamper the grinding performance and cause significant damage to the ultrasonic unit [3]. Moreover, achieving a sufficiently large vibration amplitude and stable resonance in the horn is essential for its effective application, thereby highlighting the importance of a robust horn design approach. In this context, the geometry and material of the horn also become critical, as they directly influence displacement amplification, stress distribution, and long-term durability. Although traditional horn profiles such as conical, exponential, and stepped designs have been widely adopted, they often necessitate iterative prototyping and fine-tuning to achieve the desired resonance frequency and vibration mode [4]. This limitation is further compounded by fatigue-related failures, which are frequently observed in aluminium horns due to their lower strength and fatigue resistance. To overcome these drawbacks, titanium alloys are generally preferred, since they combine superior strength, favorable acoustic properties, and high fatigue resistance. However, titanium is comparatively expensive and difficult to machine, which increases both manufacturing cost and complexity, thereby motivating the use of simulation-driven approaches to reduce design iterations and material waste. Building on this need for reliability, recent advances in finite element modelling (FEM) have provided a powerful means to predict resonant frequencies, mode shapes, and stress concentrations accurately before fabrication. By enabling such predictive capability, FEM not only reduces costly trial-and-error but also ensures that the horn resonates in the preferred longitudinal mode. As a result, the geometry and material selection can be systematically optimised to enhance durability under high cyclic stresses. Building on structural optimisation, ultrasonic systems are increasingly being coupled with sustainable cooling and lubrication

strategies to further improve machining performance. Minimum Quantity Lubrication (MQL), for example, reduces fluid consumption by supplying only a small amount of lubricant to the grinding zone. When this principle is enhanced with ultrasonic atomisation, it evolves into Ultrasonic Minimum Quantity Lubrication (UMQL), which generates ultrafine lubricant droplets capable of penetrating the grinding interface more effectively [5]. Such integration not only reduces grinding forces, heat generation, and tool wear but also contributes to improved surface finish. Furthermore, by atomising fluid into fine droplets, UMQL systems consistently demonstrate lower cutting forces and superior machining quality compared to conventional MQL approaches [6]. In parallel, it is important to recognize that a typical ultrasonic machining system generally comprises a power generator, a piezoelectric transducer, and a mechanical horn, where the horn amplifies the vibrations generated by the transducer and transmits them to the tool or workpiece. Its dynamic characteristics including resonant frequency, amplitude gain, and stress distribution directly influence machining performance [7]. Current horn designs, however, often rely on analytical approximations or empirical optimisation, which can be time-consuming and may not guarantee accurate results.

In this paper, a simulation-driven design methodology for ultrasonic horns in precision micro-grinding is presented. FEM simulations are employed to model the horn's dynamic behaviour, enabling precise tuning of its resonant frequency and mode shape, as well as optimisation of amplitude amplification and stress distribution prior to fabrication. The designed horn is subsequently prototyped and experimentally validated, ensuring consistency between simulated and practical performance. Finally, the methodology is demonstrated in the context of both Ultrasonic Vibration-Assisted Grinding (UVAG) and Ultrasonic Minimum Quantity Lubrication (UMQL) systems, highlighting its potential to advance the precision machining applications.

II. METHODOLOGY

The ultrasonic horn, also referred to as a sonotrode or concentrator, is a critical component of the ultrasonic vibration system. Acting as a waveguide, it transmits energy from the transducer to the tool or workpiece. Typically, the horn has a decreasing cross-sectional area from the input to the output end, which concentrates vibration energy and amplifies the displacement amplitude at the tip. This amplification ensures that the vibration is sufficiently large for the intended application. The design process began with basic analytical guidelines for horn dimensions and resonance. The resonance length of an ultrasonic horn is a primary design parameter, and, for a stepped horn, it corresponds to half the wavelength of the wave propagating through it [8]. Traditionally, two approaches have been employed in horn design. The first relies on analytical formulations, where mathematical relations are used to determine resonance length and geometry. However, this method can be time-consuming, requiring multiple iterations, and does not always guarantee proper tuning with the ultrasonic unit. The second and more

reliable approach is the application of the finite element method (FEM). FEM allows designers to simulate and analyse the horn's vibrational characteristics, including resonance frequency, mode shapes, and stress distribution. By iteratively adjusting horn geometry within the simulation environment, accurate tuning with the ultrasonic system can be achieved while minimising trial-and-error during physical prototyping. This study adopts the FEM-based methodology for horn design and validation. The proposed approach combines elastic wave theory, finite element simulation, parametric modelling, and experimental validation. Figure 1 illustrates the simulation driven methodology for the development of the horn. The developed methodology includes following key steps: 1. Initial design using elastic wave theory to estimate horn length and cross section for the target resonance frequency. The resonance length of the horn (L) can be calculated from the following equation [9]:

$$L = \frac{c}{2f} \qquad (1)$$

Equation 1 is used to calculate an approximate length of the stepped horn and provides the initial geometrical dimension for FEM simulation.

where c is the wave propagation velocity which is defined as:

$$C = \sqrt{\frac{E}{\rho}} \qquad (2)$$

E = Young's modulus of elasticity and ρ is the density of the horn material.
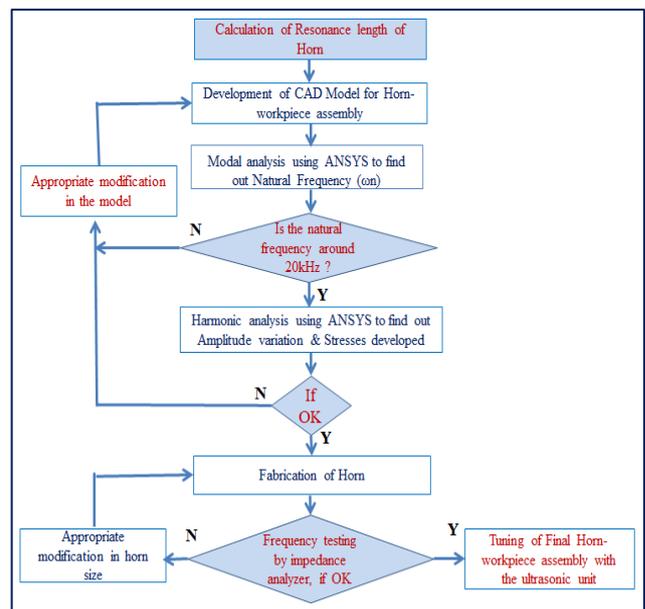

Figure 1. Simulation driven methodology for the development of the horn

Finally, the FE analysis done in Ansys Workbench environment is used to design the ultrasonic horn for providing the longitudinal vibration with a frequency of around 20 kHz. Notably, the horn- workpiece assembly is considered as one unit during the analysis. 2. Parametric modelling in CAD, allowing geometric variables to be adjusted. 3. Finite element modal and harmonic analysis to compute resonant frequencies, displacement fields and

stress distribution using ANSYS Workbench [10]. 4. Coupled horn–workpiece simulation to model the dynamic interaction under operational loads. 5. Fabrication and experimental validation using frequency analyzer, laser vibrometers or displacement sensors to measure resonant frequency and amplitude. 6. Iterative optimisation: comparison of experimental results with simulations, followed by refinement of geometric parameters until convergence.

Horns were fabricated from Ti-6Al-4V using ultra-precision machining to achieve tight tolerances and smooth surface finishes. The frequency and amplitude of vibrations were measured using an accelerometer in conjunction with a digital oscilloscope and a micro-dial gauge, respectively, and the results were compared with FEM simulations. The overall design process followed an iterative, simulation-driven approach: instead of fabricating multiple physical prototypes, the CAD models were refined, and simulations rerun until the desired performance criteria were satisfied. The final optimised horn was subsequently integrated into UVAG and UMQL systems for grinding tests on titanium alloy samples.

III. RESULTS AND DISCUSSION

The horn–workpiece assembly was modelled and meshed in ANSYS using Solid187 higher-order 3D elements, with a medium mesh density selected to balance accuracy and computational cost. Fixed support was applied at the larger horn diameter, replicating its connection with the transducer. Modal analysis was carried out to determine the natural frequencies and mode shapes of the assembly. Among the twenty modes considered, the resonance frequency was identified at 20,055 Hz in the 18th mode, which is in close agreement with the 20 kHz operating frequency of the transducer. This indicates that the designed horn is well tuned to operate in a pure longitudinal mode, ensuring effective transmission of ultrasonic energy. Harmonic response analysis was then performed using the modal results as input. Figure 2 shows the results from the harmonic analysis. With an excitation of 10 µm applied at the input end and grinding forces of 200 N (normal) and 100 N (tangential) considered, the horn achieved an amplified displacement of approximately 12 µm at the output tip. The maximum stress developed in the structure was around 205 MPa, significantly below the fatigue strength of Ti-6Al-4V (410 MPa [11]). This confirms that the horn is capable of withstanding the dynamic stresses encountered during ultrasonic vibration-assisted grinding without risk of premature failure. The combined results of modal and harmonic analyses validate the suitability of the designed horn, demonstrating both resonance compatibility with the ultrasonic system and structural integrity under operational conditions. The results demonstrate that simulation driven design enables precise tuning of ultrasonic horns and prediction of amplitude gain, stress distribution and resonance shift due to tool loading. The methodology addresses limitations of heuristic design by offering a systematic approach that can be embedded in digital manufacturing workflows. The approach also supports rapid design iterations and

customisation for different tool sizes and frequencies. Further, the resonance frequency of the fabricated horn was checked using the frequency analyzer machine with SolidSQUAD software and found to be matched with the resonance frequency of the available transducer of 20 kHz.
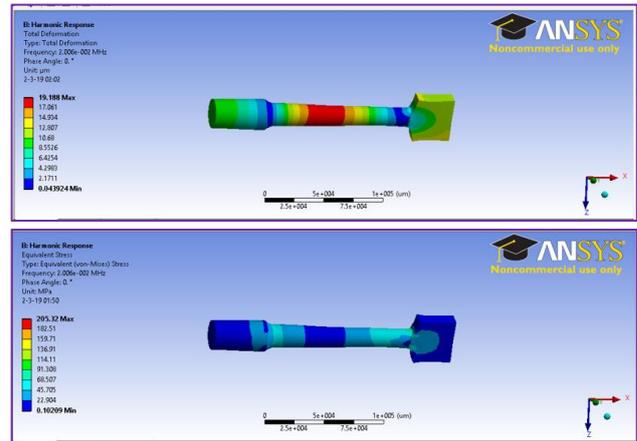

Figure 2. Harmonic response: Total Deformation, Equivalent Stress

The impedance–frequency response of the horn assembly (Fig. 3) shows a sharp minimum at ~19.96 kHz with a corresponding phase shift, confirming resonance at the design frequency. A sharp impedance minimum is clearly observed at ~20 kHz, corresponding to the resonant frequency of the horn. This resonance point aligns closely with the target frequency from FEM simulations (20.05 kHz), and the measured resonance (~19.96 kHz) confirms excellent agreement with less than 0.5% error. The narrow valley indicates a high Q-factor and efficient vibration, validating the simulation-driven design and confirming stable longitudinal mode operation.
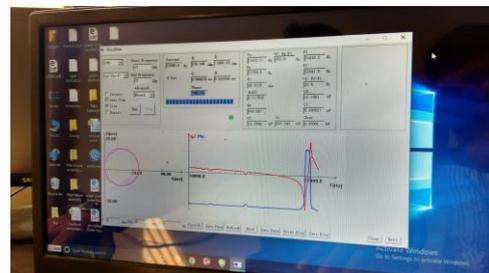

Figure 3. Impedance–frequency response of the horn assembly at ~20 kHz resonance

Further, the horn's capability was studied by conducting a demonstration of ultrasonic atomization of cutting fluid, which confirmed its effectiveness in producing ultrafine lubricant droplets. A drop of oil-based grinding fluid (vegetable oil mist lubricant) was placed at the horn tip while it vibrated at resonance. The droplet was rapidly broken down into a fine mist, visibly emanating from the tip as a fog, as shown in figure 4. This confirmed that the horn's tip amplitude and frequency are sufficient to overcome the fluid's surface tension and produce atomization. This phenomenon was captured: the fluid drop spread into a thin film on the vibrating tip and then ejected

countless micro-droplets into the air. This qualitative test is an important validation for the UMQL application. It shows the horn can serve as an ultrasonic atomizer. Prior research notes that ultrasonically atomized droplets are typically <10 µm in diameter [12]; while the droplet size was not reported in this test, the mist was very fine and consistent with effective atomization.

Figure 4. Photograph of cutting fluid droplet being atomized into fine droplets due to the ultrasonic vibration of the horn

Preliminary ultrasonic vibration-assisted grinding (UVAG) tests were conducted on a Ti-6Al-4V workpiece with the horn integrated into the grinding machine. Although a full parametric study is beyond the scope of this paper, clear improvements in grinding characteristics were observed when UVAG was enabled (20 kHz vibration on) compared to conventional grinding without vibration. These findings highlight the key advantages of the simulation-based horn design approach. First, frequency matching was achieved without the need for physical tuning cuts, thereby reducing both time and material waste. Second, stress and deformation analyses guided design refinements that enhanced reliability. Third, simulations enabled rapid evaluation of alternative horn profiles and materials. Finally, this approach reduced prototyping costs and mitigated the risk of damage to the ultrasonic system by ensuring reliable performance prior to fabrication.

IV. CONCLUSION AND SCOPE

This research developed a comprehensive framework for simulation driven design of ultrasonic horns tailored to precision micro grinding and MQL. By combining elastic wave theory, parametric CAD modelling, finite element analysis, coupled horn–workpiece simulation, and experimental validation, horns can be designed with high accuracy and efficiency. The framework enables optimisation of horn geometry for targeted resonant frequency, maximum amplitude gain and minimal stress. Experimental results confirm that UVAG and UMQL significantly reduce grinding forces, improve surface finish, and extend tool life. The results of this study highlight several key benefits of the proposed simulation-driven design framework for ultrasonic horns. The methodology aligns well with Industry 4.0 by enabling digital design, simulation, and integration with smart manufacturing systems. Future research can advance this simulation-driven design by exploring multi-dimensional vibration systems (axial-torsional or elliptical) to improve machining efficiency, and by integrating AI-driven optimization methods such as genetic algorithms or machine learning to discover novel horn geometries. The use of advanced or hybrid materials, along with additive manufacturing, could enable complex internal features and enhanced performance. Sensor integration will be key for real-time monitoring and intelligent, Industry 4.0-ready ultrasonic tools. Finally, the current framework can potentially be scaled to other applications such as drilling, milling, polishing, or higher-frequency ultrasonic processes, broadening its industrial impact.

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