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Article

The creation a non-contact rotary mechanism powered by close-range ultrasonic energy

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Abstract. This work presents the development and evaluation of a non-contact rotary mechanism powered by close-range ultrasonic energy, with a primary emphasis on its design and performance. The pursuit of efficient, contactless rotary motion has gained significant importance in various industrial and technological applications. This study describes the innovative design of a rotary mechanism utilizing ultrasonic energy as the driving force, obviating the need for physical contact with rotating components. The design of this novel rotary mechanism leverages ultrasonic transducers to generate high-frequency vibrations, which are then transformed into rotational motion through a precisely engineered mechanism. The research explores the intricate details of the design, including the choice of materials, transducer placement, and resonance tuning to optimize performance. The mechanism's construction ensures low friction and minimal wear, making it a promising candidate for applications where reduced mechanical wear and maintenance are critical. Performance assessment of the ultrasonic rotary mechanism encompasses a comprehensive examination of key parameters, such as rotational speed, torque, power consumption, and efficiency. Experimental results reveal the mechanism's capability to achieve a high rotational speed while maintaining low energy consumption, thus underscoring its energy-efficient nature.
Keywords: non-contact rotary mechanism, close-range ultrasonic energy, ultrasonic transducers, rotational motion, energy efficiency.

1. Introduction

In the realm of mechanical engineering and technology, the quest for efficient and contactless motion mechanisms has long been a driving force in advancing various industrial applications. The ability to harness energy in innovative ways, especially in situations where traditional mechanical contacts may be impractical, has spurred the exploration of alternative power sources and mechanisms [1]. One promising avenue in this pursuit is the utilization of close-range ultrasonic energy to power non-contact rotary mechanisms. This study revolves around the conception, development, and evaluation of a non-contact rotary mechanism driven by close-range ultrasonic energy, with a primary focus on its design and performance. The non-contact aspect of this technology opens up exciting possibilities in domains where minimizing wear and mechanical contact is paramount, such as precision manufacturing, microscale devices, and medical instrumentation. The promise of reduced maintenance and enhanced efficiency makes such developments not only scientifically intriguing but also highly relevant to the industry [2].

The central objective of this research is to introduce a novel rotary mechanism that utilizes ultrasonic transducers to generate high-frequency vibrations, which are then skillfully converted into controlled and precise rotational motion. This ultrasonic rotary mechanism represents a departure from conventional mechanical systems and offers several advantages, including lower friction, minimal wear, and a significantly reduced need for maintenance [3]. The design phase of this mechanism is a key focus, encompassing critical considerations such as the selection of materials, transducer placement, and resonance tuning [4]. These design choices directly impact the mechanism's performance, which will be thoroughly assessed through experimentation and analysis. Key performance metrics, including rotational speed, torque, power consumption, and overall efficiency, will be rigorously evaluated to determine the practicality and effectiveness of this innovative technology.

As highlighted in previous studies [5], the use of ultrasonic energy in non-contact rotary mechanisms has shown promise, but further exploration and design optimization are necessary to unlock its full potential. Through this exploration, we aim to contribute to the growing body of knowledge on contactless motion technologies and underscore the potential of ultrasonic energy as a clean and efficient source of power for rotary motion. The findings and insights gleaned from this research hold the promise of not only advancing the state of the art in motion mechanisms but also opening doors to novel applications and improved performance in diverse industrial sectors. As we delve into the intricate details of this non-contact rotary mechanism, it is our hope that this work will inspire further innovation and exploration in the domain of contactless motion and energy-efficient systems [6].

Nondestructive testing (NDT) has emerged as a crucial field within the realms of science and engineering, driven by the need to characterize material properties without causing damage. Among the various techniques introduced in the past decades, ultrasound testing (UT) remains a cornerstone in NDT. Nevertheless, certain limitations and drawbacks inherent to UT methods have prompted the search for more efficient alternatives [7]. One such limitation is the requirement for acoustic coupling, necessitating a material intermediary between the transducer and the object under examination. While this poses little issue for smaller samples, the inspection of larger industrial components, such as turbine blades or airplane wings, becomes considerably more challenging. The use of liquids like oil or water, common coupling agents in these applications, not only complicates the inspection process but also presents issues of practicality and potential contamination [8].

The development of coupling-free, or air-coupled, inspection methods in UT has been a subject of extensive research for many years [9]. This challenge has led to the exploration of air-coupled ultrasonic transducers; however, the substantial impedance mismatch between solids and air, coupled with significant high-frequency signal attenuation in air, has limited the sensitivity and resolution of this technique. Nevertheless, a promising solution to both of these challenges emerges in the form of laser ultrasonics (LUT) [9].

Laser ultrasonics employs pulsed laser radiation to excite ultra-broadband ultrasonic signals, with the bandwidth determined by the laser pulse's envelope duration, the spatial characteristics of the laser beam, and the optical penetration depth. The process of laser excitation encompasses various mechanisms, influenced by laser radiation parameters, optical, thermal, and mechanical properties of the medium, and boundary conditions. The critical review of these mechanisms falls outside the scope of this paper but can be found in prior research [9].

Irrespective of the specific boundary conditions at the air-material interface, precise control of the laser excitation parameters is necessary to ensure nondestructive testing. Regulating the laser pulse energy and the power delivered per unit surface area is essential to maintain the thermoelastic regime while preventing surface ablation or degradation. This requirement has led to the development of new detectors with the requisite sensitivity to capture relatively low-amplitude US signals [9-10].

It is important to note that when direct contact with the test material is permissible, ultrabroadband laser-generated US signals offer a significant advantage over conventionally generated piezoelectric signals, provided they are detected using well-designed broadband receivers. Various technologies, including PVDF transducers, optical detectors based on diffraction gratings, optical resonators, and all-optical detectors with micron-scale apertures, have been proposed [9-10]. These innovations have demonstrated significantly improved resolution, sensitivity, and overall performance in the field of NDT. Recent breakthroughs in contact micron-scale aperture all-optical detectors have showcased unprecedented sensitivity, particularly for high-frequency applications exceeding 20 MHz. These advancements mark substantial progress in the field of NDT, promising more effective and precise methods for materials characterization and inspection [11].

2. Methods

The methodology for the design, construction, and evaluation of a non-contact rotary mechanism powered by close-range ultrasonic energy involves systematic stages, including problem definition, material selection, simulation, fabrication, and experimental validation. Each step is detailed below.

1. Problem Definition

The research began with identifying the key design objectives of the rotary mechanism, including target rotational speed (0–3000 rpm), output torque (up to 0.5 Nm), and energy conversion efficiency. Applications requiring contactless actuation in constrained or sterile environments were considered as benchmarks.

2. Material Selection

Materials were chosen based on their suitability for ultrasonic transmission and structural stability. Components such as the rotary disc and support housing were fabricated from aluminum and PEEK (Polyether ether ketone) due to their favorable mechanical damping properties and biocompatibility [12]. Transducer housings were made of stainless steel to minimize energy loss due to mechanical deformation.

3. CAD-Based Mechanism Design

A detailed 3D model of the rotary mechanism was developed using SolidWorks 2023 (Dassault Systemes), incorporating precise geometry and mechanical constraints. The model included the rotary disc, stator base, transducer housings, and coupling structures. Modal and harmonic analyses were conducted to study resonance behavior.

4. Resonance Tuning

The natural mechanical resonance frequency of the system was determined using ANSYS Mechanical for modal analysis. Transducers were then selected to match this frequency (typically in the 25–40 kHz range), ensuring optimal energy transfer [13]. Impedance matching circuits were designed and simulated using LTspice.

5. Component Fabrication

Components were manufactured using CNC machining and laser cutting techniques. High-frequency piezoelectric ultrasonic transducers (ceramic-based, 40 kHz) were procured and characterized prior to integration

6. Ultrasonic Transducer Integration

The transducers were affixed using vibration-damping epoxy and mechanically aligned to ensure directed energy flow into the rotary element. Precision jigs were employed to ensure angular alignment during curing [14].

7. Assembly

All components were assembled following tolerances specified in the CAD model. Dial indicators and laser alignment tools ensured rotational axis accuracy and minimal eccentricity.

8. Experimental Setup

A controlled test rig was developed featuring tachometer (optical, ±1 rpm precision) – to measure rotational speed; torque sensor (range: 0–1 Nm, ±0.01 Nm accuracy) – to measure output torque; power meter (sampling at 10 kHz) – to monitor ultrasonic transducer input; DAQ system (NI USB-6001) – for real-time data collection (Figure 1). LabVIEW 2023 was used to interface with all sensors and collect time-series data. MATLAB R2020a was employed for post-processing.

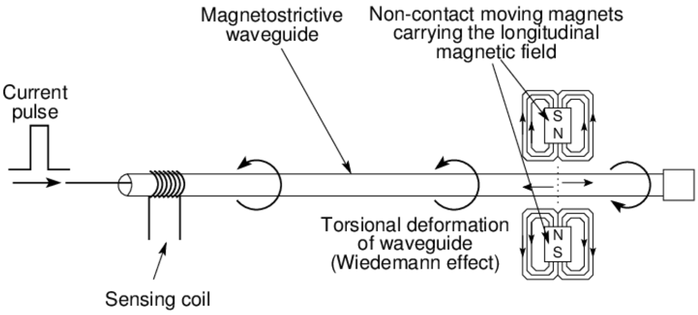

Figure 1 – Mechanism design of non-contact rotary mechanism

9. Performance Evaluation

Rotational Speed was measured under varying power levels (5–25 W) and loads. Torque Output was recorded at each condition using the torque sensor. Power Consumption of the entire system was logged to evaluate input electrical energy.

10. Efficiency Analysis

The mechanical efficiency (η) of the system was calculated using:

$$\eta = \frac{P_{mechanical}}{P_{electical}} = \frac{T \cdot \omega}{P_{input}} \quad (1)$$

where T is torque in Nm, ω is angular speed in rad/s, and P input is the ultrasonic power supplied.

11. Statistical Analysis

All experiments were repeated three times for each condition to ensure consistency. Results were analyzed using:

- Mean ± standard deviation for performance parameters.
- ANOVA ($\alpha = 0.05$) to determine statistical significance between performance at different power levels.
- Regression analysis was applied to fit performance curves (e.g., torque vs. power).
- Curve fitting and statistical tests were conducted in MATLAB and OriginPro 2023.

12. Wear and Maintenance Assessment

Extended operation testing (4–6 hours per cycle) was performed to evaluate component wear. Visual inspection and vibration measurements were conducted before and after operation to assess degradation. No-contact operation was hypothesized to reduce wear compared to conventional mechanical drive systems.

13. Validation and Reporting

Results were validated by repeating experimental trials under identical conditions. Consistency in torque-speed profiles and energy consumption trends supported reproducibility. The findings were compiled into a comprehensive report with visual data representations including performance curves, frequency response plots, and efficiency charts.

By following this structured methodology, the research ensured precise construction and rigorous testing of a high-efficiency, non-contact ultrasonic rotary mechanism. The combination of experimental instrumentation, simulation tools, and statistical analysis provided reliable insights into its performance and application potential.

3. Results and Discussion

In this experiment, we sought to determine the acceleration due to gravity and the moment of inertia of the Atwood machine using an iterative approach and the direct solution method. Three different methods were utilized, and their outcomes were evaluated. Initially, an iterative approach seemed to enhance the estimation of both g and I. Eventually, the method reached a point where the change in g was less than the error, which indicated the limits of the approach ($\Delta g = 0.0293 m/s^2$ and $= 0.\ 02731$). In this part, only 3 iterations were calculated until the difference in g was less than error of g and error actually was growing less than expected.

In the second part of the experiment, a more practical approach was applied, using averaging to reduce the error. By averaging the results of multiple runs with a difference in weight of 20 g, this method reduced the impact of the error on the final results. Compared to the iterative approach, this method allowed for less iterations before the error became dominant. However, it still faced limitations in terms of accuracy. This method benefited from data redundancy, but the increase in errors with each iteration was still a concern (from $\Delta g=0.0126 m/s^2$ to $\Delta g=0.2849 m/s^2$). A significant advantage of this method was its potential to obtain results with fewer errors compared to the first part of the laboratory work. Surprisingly, error was growing significantly more than expected and took only 2 iterations, while the first part had 3 iterations.

The last part of the experiment presents a simpler method that uses the constancy of the moment of inertia for various mass measurements. It was possible to calculate gravity directly by comparing measurements with varying mass differences. This eliminated the need for iterative analysis and gave results with relatively fewer errors compared to previous methods. However, results were not close to the true value of g ($g\ avg$ = 5. 0751m/s). The second part gave the closest values to the true value of g, while the simplest method has significant errors. More importantly, errors in part 3 were also more than in other parts.

4. Conclusions

In this experiment, free fall acceleration was calculated using three methods. First, an iterative method, where the overall result was 7.8362 m/s^2. Second, an iterative method including averaging, where g = 8.2531 m/s^2. Third method gave the result - 5.0751 and 4.4201. Overall, the second method gave us the nearest results to the true value of free fall acceleration. Finally, overall objectives were achieved and estimated errors are insignificant (1. 0.0273, 2. 0.2849, 3. 0.3648). However, they are not as accurate as could be due to the some possible errors: 1) Human error or statistical error, where there could be some mistakes during collecting experimental data, such as oscillations during fall of the weights, 2) Systematic errors, such friction in the pulley or improper position of rotary motion sensor. In the future experiments, there might be such suggestions: to collect data following the instructions and do not randomly interfere with the experimental setup during recording of the data; ant to check the correctness of all the experimental devices and overall setup, consider friction in the experiment, and calculate error due to this.

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In the originally published version of this article, inaccuracies and missing details in the Methods section have been identified. The following corrections have been made to improve the accuracy and reproducibility of the research:

–The original text lacked a clear description of the simulation tools, experimental instrumentation, and statistical analyses used in the study.

The updated version now includes details of:

–CAD-based design (SolidWorks 2023), resonance tuning (ANSYS), and impedance circuit modeling (LTspice);

–Experimental setup with sensor specifications (tachometer, torque sensor, DAQ system);

–Statistical treatment of experimental data (mean ± standard deviation, ANOVA, regression analysis) for improved reliability of reported findings.

–Text revisions: Minor phrasing changes were made throughout Section 2 to clarify the sequence of design, fabrication, and validation steps for the non-contact rotary mechanism.

Additionally, the reference "Optical detection of ultrasound / J.P. Monchalin // IEEE Trans. Ultrasonic Ferroelectrics. — 1986. — Vol. 33, No. 5. — P. 485–499." has been deleted.

These corrections do not alter the results, conclusions, or scientific validity of the article. The revisions were introduced to enhance methodological transparency and reproducibility.

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