Design and testing of a novel rotary transformer for rotary ultrasonic machining

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Abstract: This paper presents the design and testing of a novel rotary transformer for rotary ultrasonic machining (RUM). The transformer structure is innovatively designed for easy assembly and disassembly, which provides increased convenience to tool replacement in RUM. Circuit analysis shows the efficiency loss caused by the structure simplification is less than 5%. Also, the effect of the primary core angle and air gap length on coupling coefficient is studied for guiding the design. A rotary transformer with 90° primary core and 1.0 mm air gap is achieved. Contrast tests were carried out in simulation and experiment. Results show this novel rotary transformer transmission efficiency is 0.8972, which is agree with the theoretical value.

Keywords: rotary transformer, structure design, circuit analysis, flexibility, rotary ultrasonic machining
Classification: Power devices and circuits

References
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1 Introduction

With the distinct advantages of high material removal rate, low cutting force, long tool life and good surface quality, rotary ultrasonic machining (RUM) is widely used in the processing of hard and brittle materials [1, 2]. Nowadays, in RUM, the most common way to transmit electrical energy from power supply to rotatable transducer is by sliding contacts, usually brushes and slip rings [3]. However, the lifetime of this kind of device is strongly related to the cumulated number of revolutions. The friction between slip rings and brushes leads to abrasion and temperature rising [4, 5]. What’s more, any fault on electrical contact can generate sparks [6], so such machines cannot be installed in flammable and explosive environments.

Rotary transformer can be used to replace the brushes and slip rings. As the key component of a contactless energy transfer system (CETS), a rotary transformer is usually composed of two windings and corresponding cores. Rotary transformers have numerous applications such as electric vehicle, bio-engineering devices, and handheld devices[5, 7, 8]. According to the structures, commonly used rotary transformer can be divided into three types and in order to reduce leakage and magnetizing energy, the air gap between two cores is small (usually 0–1mm). The structural sketches are shown in Fig. 1.
In RUM, tool replacement is realized replacing tool handle together with the tool, so the two sides of rotary transformer needed to be assembled and separated frequently. A slight jitter of the spindle or a human error in the assembly process may lead to a collision between the cores, causing serious safety problems. In other words, these rotary transformers raise the operational accuracy requirements and bring a lot of inconveniences to tool replacement in RUM.

In this paper, we propose a rotary transformer with simplified primary side for easy disassembly. Differing from conventional rotary transformers, the primary side of this rotary transformer is part of ring rather a full ring, so the primary side and the secondary side can be easily assembled and separated. This structural optimization can significantly improve the flexibility of the RUM vibration system, reduces the assembly accuracy requirement and simplifies the tool replacement process. By analyzing the affecting regularity of primary core angle and air gap length on coupling coefficient, a set of parameters is determined. A rotary transformer is assembled and tested. The transmission efficiency of a CETS with this rotary transformer is about 0.9, which is verified experimentally.

2 Structure design and configuration

In RUM, different processing stages need different types of tool, the rotatable part need to be installed and removed frequently. Conventional rotary transformer with 360° cores can only be separated along axial direction. However if the primary core simplified to no greater degrees 180°, the flexibility will be significantly improved. The sketch of CETS with this simplified rotary transformer for RUM is showed in Fig.2. The lower left of Fig.2 shows the configuration of this simplified rotary transformer, including two windings and two corresponding ferrite cores. The primary winding is wound around the primary core. The secondary winding is laid in the groove of the secondary core ring. The windings are copper litz wires, and the number of coil turns is 40 (primary) and 30 (secondary). The physical separation of the rotatable transformer is ensured by adding a small air gap between the ferrite cores. The primary core angle $\alpha$ and the air gap length $l$ are two key parameters having close relationship with the performance of a rotary transformer. The selection of the value of $\alpha$ and $l$ is discussed in section 4. The remaining dimension parameters of the model are designed according to a standard specification of tool handle (bt40), so that this rotary transformer can be easily installed to a handle for machining application.
The primary winding is connected with the ultrasonic power and the secondary winding is connected with the transducer. Ultrasonic energy is transmitted to the transducer based on local electromagnetic induction effect without physical contact. Moreover, this rotary transformer permits easy disassembly to RUM vibration system. When the tool needs to be replaced for different producing process, the static part can be moved apart in radial direction in advance, and then the rotatable part be removed from machining center in axial direction without causing collisions. So this novel rotary transformer greatly reduces the operating accuracy requirement and shortens the time-consume in tool replacement process.

3 Magnetic reluctance circuit and theoretical analysis

The magnetic reluctance circuit of a CETS for RUM is depicted in Fig.3-a [5]. $L_P$ and $L_S$ are inductances of the coils, $R_P$ and $R_S$ represent the AC resistances. $M$ is the coefficient of mutual induction. $R_L$ represents equivalent impedance of mechanical load. The capacitance of the piezoelectric is represented by $C_0$ and the dielectric loss is reflected by $R_0$. $L_i$, $C_i$, $R_i$ are the transducer’s mechanical behavior, represent mechanical vibration system’s mass, stiffness and damping. In the equivalent circuit, the leakage flux is represented as leakage inductance which inevitably exchanges plenty of reactive power. Therefore, compensations $X_P$ and $X_S$ (capacitance) are series connected to the circuit to set the reactance equaling to zero. So the magnetic reluctance circuit was simplified to Fig.3-b.
To maximize electro-acoustic efficiency and vibration amplitude, the system is set to operate at series resonance frequency \( \omega_s = \frac{1}{\sqrt{L_s C_s}} \). The resistance and reactance of ultrasonic vibration system at series resonant frequency are given as:

\[
\begin{align*}
R_T &= \frac{R_i + R_f}{\omega_s^2 C_0^2 (R_i + R_f)^2 + 1} \\
X_T &= -\frac{\omega_s^2 C_0 (R_i + R_f)^2}{\omega_s^2 C_0^2 (R_i + R_f)^2 + 1}
\end{align*}
\]  

(1)

With the assumption that the circuits are under complete compensation and no-load, when considering the secondary circuit as the electrical load of the primary circuit, the transmission efficiency of the system can be derived as:

\[
\eta = \eta_p \times \eta_s = \frac{R_{RC}}{R_p + R_{RC}} \times \frac{R_f}{R_s + R_f}.
\]

(2)

In which, \( R_{RC} \) is the reflected resistance which represents the impact of secondary circuit on primary circuit. As \( R_{RC} \) is derived as \( R_{RC} = \frac{\omega_s^2 M^2}{R_s + R_f} \) [10], so the transmission efficiency of the CETS can be defined as:

\[
\eta = \frac{1}{R_p (R_f + R_s) + 1} \times \frac{R_f}{R_s + R_f}.
\]

(3)

In Eq. (3), the efficiency of the CETS is expressed as two formulas in multiplication. The structure of the primary winding and core change will just affect \( M \) and \( R_p \), the formula \( \frac{R_f}{R_s + R_f} \) remains unchanged. When the primary core changes from a whole core to a portion of a ring, \( R_p \) and \( M \) will decrease, because of \( M \) squared in the formulas, \( M \) decrease impact more on the value, so the value of formulas \( \frac{R_p (R_s + R_f)}{\omega_s^2 M^2} \) increases, \( \eta \) will decrease. Whereas, because of the
difference in magnitude of numerator and denominator, the value of \( \frac{R_p(R_T + R_S)}{\omega_S^2M^2} \) usually less than 0.05. Consequently, compared with a 360° rotary transformer, the efficiency loss of proposed rotary transformer in section 2 is less than 5%.

4 Structure optimization

Coupling coefficient \( k \) of a transformer is a key parameter affecting the efficiency of a CETS. Although circuit compensation can alleviate the problems associated with large air gap, low coupling coefficient of the contactless transformer is still the bottleneck limiting the efficiency of a CETS [9, 11, 12]. The primary core angle \( \alpha \) and the air gap length \( l \) are two key parameters, which are closely related to the coupling coefficient \( (k) \) of a rotary transformer. To obtain a rotary transformer with better flexibility as well as higher \( k \), we calculated the impact of \( \alpha \) and \( l \) on \( k \) using Ansoft. Situations are researched where six kinds of primary core angle(30°, 60°, 90°, 120°, 150°, 180°) with air gap length varying from 0.02mm to 5mm are considered. The variation trend of coupling coefficient \( (k) \) is shown in Fig.4.

![Fig. 4. Variable trend of (a) coupling coefficient \( k \) (b) first derivative of \( k \)](image)

Fig.4 shows the variation tendencies of \( k \) and first derivative of \( k \), clearly showing
how \( k \) is affected by \( \alpha \) and \( l \), so that we can determine which point is a better choice. First derivative of \( k \) reflects the change speed degree of \( k \) more clearly. It can be seen from the result in Fig.4(a), large primary angle \( \alpha \) and small air gap length \( l \) will both result in high coupling coefficient \( k \). But small \( \alpha \) and \( l \) reduces the flexibility, because large \( \alpha \) core has large volume, so more workspace is needed for separation; also small gap increases the operational accuracy requirements. So there is a contradiction between high coupling coefficient and structure flexibility. Although we cannot achieve best flexibility and highest \( k \) at the same time, we can obtain a relative optimal structure in comprehensive coordination of flexibility and coupling coefficient.

The air gap length is crucial to the magnetic components’ operation, a longer air gap results in more energy loss than a short or no air gap, an air gap between 0mm-1mm is recommend[9]. And in many references[4,8,12], the rotary transformers are optimized with a gap in the range of 0mm\(< l \leq 1\text{mm}. As there is no much difference in design principle of rotary transformer air gaps, 0mm\(< l \leq 1\text{mm} is also appropriate for design in this paper.

In fig.4, with the \( l \) increasing in the range of 0mm\(< l \leq 1\text{mm}, the k of the rotary transformer decreases in exponent, and the decrease is becoming more intense with primary core angle reduction. In the range of \( l > 1\text{mm}, the decline tends to linear, which is more directly shown in Fig.4-b. The change of the trend has something to do with the core shape and the arrangement of coils. Because the primary core is a portion of ring and the coils is wounded around the primary, the primary winding is not in regular shape. When \( l \) is small \( (l < 1)\), the leakage exist in both the gap area and the area of core ends. When \( l \) get large \( (l > 1)\), magnetic intensity rapid decline in the area of two ends of arc core, the leakage is mainly come from the gap area, so the trend become orderly. This also why a small \( \alpha \) has relatively longer exponential decrease process than a large \( \alpha \) in fig .4. In RUM, there might be a small-amplitude vibration (small than 0.1mm) on the machine caused by the spindle rotation, which may slightly change the air gap length. So, an air gap \( l \geq 1\) is more preferable where \( k \) is less sensitive to \( l \) change.

Similarly, as shown in fig.4, small \( \alpha \) will seriously restrict \( k \), so \( \alpha \) less than 60° are not recommended. When \( \alpha \) is over 120°, the lines get even closer, the rate of \( k \) increase is much lower than the rate of degree increase, the promotion of \( \alpha \) increase to \( k \) is limitedly. As for flexibility, workspace is considered as one of the important indexes for evaluating the device. A core with large \( \alpha \) has large volume, needing more workspace during separation; also by calculated the ratio of rate of \( k \) increase by rate of volume increase at \( l=1\text{mm}, 90^\circ \) has the highest value (0.245), which means among six core angle discussed, when the primary is 90°, it has the highest benefit on \( k \) with the volume increase.

Considering all the above-mentioned factors synthetically, \( \alpha=90^\circ, l =1.0 \text{ mm (the point indicated by the arrows in Fig.4-a) is selected as a relative optimal design parameters, then a rotary transformer is fabricated.}

5 Performance testing and comparison

Simulation and experiments were done to further determine the electrical
performance of this rotary transformer. Finite-difference time-domain (FDTD), finite element method (FEM) and hybrid method of moments (MoM) have been widely used in calculation and field analysis [13]. Ansoft is a software based on FEM, which is appropriate choice for circuit simulation [8].

In simulation, a transient field is calculated by using Ansoft, the magnetic field distribution and current density distribution are shown in Fig.5.

From the field distribution results, we can see the windings are in good mutual inductance effect. The primary core is a portion of ferrite ring, so on the secondary core only the part faced to the primary core is ‘effective area’, the magnetic induction line go through the primary core and effective area in secondary core, achieving a closed loop. At the edge of effective area, the magnetic line become somewhat divergent. From the current density distribution, the distribution of current is uniform. The transmission efficiency obtain from simulation is 0.9050, and more detail data is listed in Table I.

In the experiments, as shown in Fig.6, two digital power meters were used to directly measure the power of the power supply and the transducer, so the efficiency was easily calculated. The practical performance of this optimized transformer was obtained, which can be a comparison to simulation results. Furthermore, a conventional rotary transformer was assembled, the performance of this transformer was also obtained as control. Detailed data is listed in Tab. I.
Theoretical efficiency of the CETS with this two rotary transformers, calculated with Eq. (3), are 92.09% for 360°, 91.10% for 90°, the difference is 1.07% less than 5%. Simulation result and experimental results are close in value, but slightly lower than theoretical value. This is because the theoretical value is based on fully-compensated circuits, which is hardly to achieve in reality. Taking the deviation of compensation into account, the experiment result is agree with theoretical values. Experimental results indicate that the performance of this novel transformer is close to that of a conventional one’s, two transformers both have high efficiency. The difference between two efficiency values is 1.47%, also less than 5%. This also verified the theoretical analysis in section 3. With both high flexibility and good performance, this novel rotary transformer can well meet practical application requirements in RUM.

6 Conclusion
This paper presents the design and testing of a novel rotary transformer for RUM. The benefits brought by this rotary transformer to RUM is discussed. Circuit analysis shows the efficiency loss caused by the structure simplification is less than 5%. The relationship among primary core angle, air gap length and coupling coefficient is studied. A novel rotary transformer with 90° primary core angle and 1mm air gap length is presented for easy disassembly. The performance this rotary transformer has been confirmed in both simulations and experiments, the coupling coefficient is 0.66 and the transmission efficiency is about 0.9. This rotary transformer is a better replacement of slip rings and conventional transformers in RUM as well as other applications where device is desired to install and remove frequently.

The work in this paper also inspire that it is unwise to pursue an excessive coupling coefficient of a rotary transformer in some applications. Optimizations in structure, size or weight can be achieved with just a small loss in efficiency, which are more valuable in engineering application.

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<th>Table. I Simulation and experiment results</th>
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