Zhe Du, Rui Guo and Zhi-Gang Hu*

Modeling and Testing of an ICPTs Used in Dynamic Balancing Device

Abstract: In order to balance the out-of-balance mass and reduce the harmful vibrations of motorized spindles, author developed a novel dynamic balancing device of standing-wave piezoelectric motor type with both simple and reliable structure. Since the whole balancing device is mounted on rotor of the spindle and rotating synchronously with it, this paper examines the possibility of using specially designed ICPTs to deliver electrical energy from stationary position to the balancing device with help of a novel contactless rotatable transformer.

Keywords: Contactless rotatable transformer, ICPTs, Compensation, Ferrite material

1 Introduction

Today, majority of machine tool systems are equipped with motorized spindles to improve the machining efficiency and precision, and one of the important consideration for speedup of spindles is the harmful vibration due to out-of-balance mass. Therefore, it is particularly necessary to balance these spindles at running state, as carefully as possible, to ensure smooth running. Up till now, various balancing systems have been developed to balance the out-of-balance mass in order to reduce the harmful vibrations [1-4]. Recently we also developed a novel dynamic balancing device of standing-wave piezoelectric motor type with both simple and reliable structures. This device can be used for effectively reducing the out-of-balance mass in a running motorized spindle to a relatively low level, and try not to influence the spindle’s rotation characteristic in the meantime. Because the balance device has two sets of adjusting mechanism, two high-frequency AC power are required and need to be controlled with the electrical energy. Since the whole balancing device is mounted on rotor of the spindle and rotating in synchronous with it, it is evident that conventional electrical connection solutions such as trailing leads, rolling/sliding carbon/metal contacts can’t meet the requirement of power transmission. In this paper, a specially designed inductively coupled power transfer system (ICPTs) is employed to deliver electrical energy from stationary position to the high-speed
rotating balancing device with help of contactless rotatable transformer, which is the kernel of the whole ICPTs that can transmit electrical energy without any mechanical contact. So far a number of contactless rotatable transformers have been described in literatures [5-10]. In contrast with these rotatable transformers generally consisting of a set of pot cores with a winding fitted into each of them, the one we investigated consists of two set of cores that can be thought of as an extended “C” core, with a winding running around the entire length of each of them in order to transmit two ways of high-frequency AC power alternately.

Due to the physical separation between the windings, and the availability of alternative magnetic-flux paths (air gap) rather than the ideal core path, the rotatable transformer exhibits relatively large leakage inductances and significantly reduced magnetizing inductance between the primary and the secondary, resulting in low gain and high loss for the ICPTs. Therefore, to solve the problem of poor efficiency of the ICPTs directly and effectively, a suitable impedance-matching circuit in the primary and secondary of the rotatable transformer making the compensated circuit operate at resonant frequency can be adopted in order to achieve the maximum system output power under the minimum system input VA rating.

In section 2 of this paper, the operation mechanism of the dynamic balancing device and the structure of the contactless rotatable transformer are introduced briefly. Section 3 presents the system modeling and compensation topology analysis of the ICPT system in detail. And then, section 4 determines the turns of the rotatable transformer windings based on previous section analysis, and derives inductance measurement of the contactless rotatable transformer. At last, the preliminary analysis on the experiment results of a prototype system and the conclusions are given in section 5 and section 6 respectively.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_e$</td>
<td>Equivalent inductor of series subcircuit of the piezoelectric actuator</td>
</tr>
<tr>
<td>$C_e$</td>
<td>Equivalent capacity of series subcircuit of the piezoelectric actuator</td>
</tr>
<tr>
<td>$R_e$</td>
<td>Equivalent resistance of series subcircuit of the piezoelectric actuator</td>
</tr>
<tr>
<td>$C_d$</td>
<td>Clamping capacity of the piezoelectric actuator</td>
</tr>
<tr>
<td>$f_p$</td>
<td>Parallel resonance frequency of the piezoelectric actuator</td>
</tr>
<tr>
<td>$f_s$</td>
<td>Series resonance frequency of the piezoelectric actuator</td>
</tr>
<tr>
<td>$\omega_s$</td>
<td>Series resonance angular frequency of the piezoelectric actuator</td>
</tr>
<tr>
<td>$U_p$</td>
<td>Primary input high frequency sinusoidal voltage</td>
</tr>
<tr>
<td>$U_0$</td>
<td>secondary output high frequency sinusoidal voltage</td>
</tr>
<tr>
<td>$I_p$</td>
<td>Primary input high frequency current</td>
</tr>
<tr>
<td>$I_s$</td>
<td>secondary output high frequency current</td>
</tr>
</tbody>
</table>
### Symbol Explanation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_p$</td>
<td>Primary self-inductance of the inner ring transformer</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Secondary self-inductance of the inner ring transformer</td>
</tr>
<tr>
<td>$M$</td>
<td>Mutual inductance of the inner ring transformer</td>
</tr>
<tr>
<td>$R_p$</td>
<td>Internal resistance of primary winding of the inner ring transformer</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Internal resistance of secondary winding of the inner ring transformer</td>
</tr>
<tr>
<td>$R_d$</td>
<td>Equivalent resistance of the piezoelectric actuator</td>
</tr>
<tr>
<td>$X_d$</td>
<td>Equivalent reactance of the piezoelectric actuator</td>
</tr>
<tr>
<td>$Z_s$</td>
<td>Total impedance of the secondary circuit</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Compensation capacity of the primary circuit</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Compensation capacity of the secondary circuit</td>
</tr>
<tr>
<td>$Z_r$</td>
<td>Reflected impedance of the secondary circuit exerts on the primary</td>
</tr>
<tr>
<td>$R_r$</td>
<td>Reflected resistance of the secondary circuit exerts on the primary</td>
</tr>
<tr>
<td>$X_r$</td>
<td>Reflected reactance of the secondary circuit exerts on the primary</td>
</tr>
<tr>
<td>$Z_p$</td>
<td>Total impedance of the primary circuit</td>
</tr>
<tr>
<td>$L_{diff}$</td>
<td>Differential inductance</td>
</tr>
<tr>
<td>$L_{cum}$</td>
<td>Cumulative inductance</td>
</tr>
</tbody>
</table>

## 2 Contactless Power System Description

### 2.1 Operation Mechanism of the Dynamic Balancing Device

First of all, we want to briefly introduce the operation mechanism of the dynamic balancing device. Each device includes two sets of edge-driving piezoelectric actuators in the same form. A set of piezoelectric actuator consists of annular rotor and piezoelectric stator. The configuration of a set of piezoelectric actuator under consideration is shown in Fig.1 (A). An in-plane bending vibration $B_{32}$ mode of the annular plate made of aluminium is used as the resonance mode of the stator vibrator. Fig.1 (B) shows polarization division arrangement of the piezoelectric ceramic disk for driving. The annular piezoelectric ceramic disk with six polarization partitions is bonded to the annular aluminium plate; both together make up a stator. Six projecting teeth are installed at the external circumference side of the annulus aluminium plate and located at certain positions. The rotor, with a thin frictional material bonded on its internal circumference side, is installed on the outside track of the stator. Through an appropriate preload force, the internal circumference side of the rotor and the external circumference side of the six teeth contact with each other. When AC power in specific frequencies is applied on the six electrodes of the stator, an ideal in–plane bending vibration mode will be excited as a result of the inverse
piezoelectric effect. The teeth in contact with the rotor will vibrate in the radial and circumferential directions due to the vibration mode. Then a circumferential frictional force creates under the radial pressure between the teeth and the rotor, which will drive the rotor rotating along the circumferential direction. On account of the pre-installed counterweight mass on the rotor, the motion of the rotor can realize regulation balancing role.

Fig. 1: Structure diagrams of the dynamic balancing device
The Electromechanical equivalent circuit of the piezoelectric actuator of the dynamic balancing device is similar as the well-known piezoelectric ultrasonic transducer, which is composed of a series sub circuit of equivalent inductor \( (L_e) \), equivalent capacity \( (C_e) \) and equivalent resistance \( (R_e) \) and a parallel branch of clamping capacity \( (C_d) \), as shown in Fig.2, which represents the electromechanical behaviour of the piezoelectric actuator [11, 12]. The \( C_d \) can be measured at the frequency far away from resonant frequency, which approximates to static capacity; the other values can be simply obtained from calculation of the impedance data.

![Fig. 2: The Electromechanical equivalent circuit of the piezoelectric actuator](image)

The impedance characters of the piezoelectric actuator have been measured by a Frequency Response Analyser (FRA), as shown in Fig.3. According to the Fig.3, the various parameters can be obtained directly or further derived as shown in Tab.1:
Fig. 3: Impedance characters of the piezoelectric stator at 55 kHz to 80 kHz frequency band

Tab. 1: Parameters of the piezoelectric actuator

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Acquisition method</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_d</td>
<td>Measured by capacitance meter</td>
<td>25nF</td>
</tr>
<tr>
<td>f_s</td>
<td>Obtained directly by Fig.3</td>
<td>66.96kHz</td>
</tr>
<tr>
<td>f_p</td>
<td>Obtained directly by Fig.3</td>
<td>67.94kHz</td>
</tr>
<tr>
<td>R_e</td>
<td>Obtained directly by Fig.3</td>
<td>115Ω</td>
</tr>
<tr>
<td>L_e</td>
<td>1/(4n2fs2Ce)</td>
<td>7.53mH</td>
</tr>
<tr>
<td>C_e</td>
<td>[(fp2/fs2)-1]Cd</td>
<td>0.75nF</td>
</tr>
</tbody>
</table>

2.2 Contactless Rotatable Transformer

As the introduction mentioned, the contactless rotatable transformers is the kernel of the whole ICPTs that can transmit electrical energy without any mechanical contact. The principle of transformer working on the electromagnetic induction is similar to the conventional transformer except that a large air gap between the primary and the secondary is arranged to enable the rotation of a part of the structure [8, 13].

A mechanical layout is proposed for the rotatable transformer as shown in Fig. 4. In order to transmit two high-frequency AC power, two sets of transformers are installed in a set of stepwise substrate. We call them the inner ring transformer and the outer ring transformer respectively. (The shape is designed in stepwise as to
increase the air gap distance between the inner and outer ring transformer.) The stationary halves of the substrate are fixed on end cap of the spindle, and the rotatable one is mounted on the rotor of the spindle with dynamic balancing device. The primary core halves and windings are installed in the stationary substrate, and their counterparts, the secondary core and windings are installed in the rotary substrate.

**Fig. 4:** Profile chart of the contactless rotatable transformer

**Fig. 5:** Photo of the contactless rotatable transformer without assembly

When transmitting high-frequency AC power, the conventional contactless transformer core is constructed in two ways, one is in use of high-temperature sintering ferrite cores [7, 8, 13], and the other is the use of air core (coreless) [14-16]. Based on the geometry of core is relatively small with thin wall in our study, high-temperature
sintering ferrite core is prone to sintering deformation, and thus cannot meet the requirements of geometric accuracy. Furthermore, since the resonant transmission frequency of the system is relatively low, the air core will result in low transmission efficiency. Taking into account the two issues above, a room temperature vacuum curing of ferrite core material is proposed, and the formulation of this material is given by Tab.2.

**Tab. 2: Ingredients of the core material**

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Epoxy</th>
<th>dimethylbenzene</th>
<th>Curing agent</th>
<th>Ferrite powder</th>
<th>Iron powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight ratio</td>
<td>10%</td>
<td>3.3%</td>
<td>10%</td>
<td>10%</td>
<td>66.7%</td>
</tr>
</tbody>
</table>

After real test, the relative permeability of this ferrite core material is 9.3.

This kind of self-made ferrite core material has been chosen for our research due to its merits in comparison with the traditional ones, which are as follows:

- Good performance of later machinability. The dimensional tolerances of the post-processed cores meet the requirements;
- Relatively high magnetic permeability. Coupling efficiency can be improved;
- Relatively light weight, can reduce the influence of the rotational properties of the spindle;
- Directly curing and processing in the substrate, this can avoid secondary bonding and improve the overall safety.

In help of this design, the windings of transformer in two circumferences can be separated and it can provide good path for the magnetic flux. Due to advantages of this structure, we will ignore the interference between the inner ring transformer and the outer one temporarily in the research work after, and take the inner transformer as the major study object.

Unlike the traditional method, during which the specific parameters of transformer windings were determined by reluctance method and/or empirical formula [31, 32], in our study, the parameters for transformer windings can be obtained according to the practical need of the ICPTs after the compensation topology research.

### 3 System Modeling and Compensation Topology Analysis

Among the literature proposed so far, a typical ICPT system consisting of converter, compensated circuits in the primary and secondary sides, inductive transformer and
DC converter is most commonly seen [17-23]. The structure of the ICPT system is shown in Fig.6.

Fig. 6: Block diagram of a typical ICPTs

In this paper, the investigated ICPTs, as shown in Fig.7, employs a high frequency AC power to generate a standard sinusoidal voltage of Specific frequency. This voltage is fed to the rotatable transformer primary after primary compensation. The secondary transformer is connected to the special load--the dynamic balancing device directly to supply its power after secondary compensation. Due to the special load is driven by the high frequency sinusoidal voltage directly, so AC-to-DC converter is no longer need in secondary side of the ICPTs.

Fig. 7: Block diagram of the investigated ICPTs

To determine the characteristics of the ICPTs, the fundamental mode analysis (FMA) can be often used [24-26], which provides a much simpler and more intuitive analysis approach by modelling the resonant circuit in terms of the fundamental mode of the circuit waveforms, and thereby avoid mathematically complex from requiring a numerical solution to a large number of simultaneous transcendental equations. At the same time, mutual inductance modelling method [24, 25, 27] is adopted in this paper, to analyse the coupling effect of the contactless rotatable transformer. In the
mutual inductance model, the induction voltage and reflected voltage are used to describe the coupling effect. The two concepts are expressed by mutual inductance. The reflected voltage shows the whole influence from secondary winding on primary winding. So it is not necessary to divide mutual inductance from leakage inductance.

The whole system model without compensation, as shown in fig.8, includes three parts. The first part is an AC power model that represents the high-frequency AC power. The second part is a transformer model that describes the relationships between the fundamental components related to the contactless transformer circuit. The resistance and inductance values of both sides are respectively $R_p$, $L_p$, $R_s$, and $L_s$, and $M$ is the mutual inductance. The inductive voltages in primary and secondary circuits are respectively $-j\omega s M I_s$ and $j\omega s M I_p$. Power transmission is realized during the process of inducing voltage mutually. The third part is the electromechanical equivalent model of the piezoelectric actuator, which describes the load characteristics of the ICPTs.

(A)

Fig. 8: Simplified circuit model of the ICPTs
As the contactless rotating transformer has the characteristics of relative large leakage inductance and low magnetic inductance, and the system is highly reactive due to the high transmission frequency, the power transfer efficiency is poor. In order to improve the power transfer efficiency of the whole system, an efficacious approach using impedance matching to compensate the reactive power for the primary and secondary circuits respectively is necessary. The primary compensation can make the ICPTs ideally operating near zero phase angles between the primary input voltages and current at a locked frequency in order to minimize the VA rating of the supply, thus the power factor and supply quality can be meliorated. At the same time, the output power and transmission efficiency can be improved by the secondary compensation [24, 25, 27]. In further studies, the system circuit model and the compensation topology analysis will be implemented synchronously, and the process of analysis will be derived in reverse direction (from the secondary side to the primary side of the ICPTs).

In this paper, the nominal resonant transmission frequency of the ICPTs depends on the inherent frequency of the piezoelectric actuator. In order to produce the desired vibration mode and maximize efficiency of the piezoelectric actuator, its inherent frequency should be defined at series resonant frequency of a corresponding vibration mode. As mentioned above, the series resonance frequency \( f_s \) of the piezoelectric actuator can be obtained by real test. When the piezoelectric actuator
is operated at this frequency, its present dynamic sub-circuit state of pure resistance and electromechanical equivalent circuit can be simplified, as shown in Fig.9 (A). In order to facilitate further analytical work, it can be continued to transform into the standard impedance model, as shown in Fig.9 (B).

The equivalent resistance ($R_d$) and reactance ($X_d$) of the piezoelectric actuator can be obtained as:

\[ R_d = \frac{R_x}{1 + \omega_s^2 C_d^2 R_x^2} \]

\[ X_d = -\frac{\omega_s C_d R_x^2}{1 + \omega_s^2 C_d^2 R_x^2} \]

Therefore, when the piezoelectric actuator operates in series resonant frequency, the system secondary circuit is equivalent to the Fig. 10:

![Fig. 10: Secondary circuit model without compensation](image)

![Fig. 11: Secondary circuit model with compensation](image)
The expression of total impedance of the secondary circuit can be given by:

\[
Z_s = R_s + \frac{R_s}{1 + \omega^2 C_d^2 R_s^2} + j\omega_s \left( L_s - \frac{R_s^2 C_d}{1 + \omega^2 C_d^2 R_s^2} \right)
\]  (3)

Considering the above expression, it can be seen that the secondary circuit is highly reactive under high operational frequency. Thus if the secondary winding is connected directly to the piezoelectric actuator, reactive power loss of the secondary circuit must be greatly increased. Finally, it will become a reality that the power transfer capability cannot meet the requirements. For this reason, it is very necessary to employ secondary compensation to boost the power transfer capability from the primary to the secondary. As a result, there is no limit to the power transfer capability because the series compensated secondary is a voltage source in effect driving into the piezoelectric actuator at its series resonant frequency, and making the output voltage independent of the load and equal to the secondary open circuit voltage.

According to the circuit designed by us, the secondary circuit is inductive under no compensation, so \( L_s \) must be more than \( \frac{R_s^2 C_d}{1 + \omega^2 S^2 L_s^2} \). So far, the specific design parameter of the self-inductance of the secondary winding of the inner ring transformer has been determined, and can be complied in processing the transformer in next section.

Due to the designed secondary circuit is inductive, it is necessary to add compensation of series capacitance. The secondary compensation topology can be shown in Fig.11.

As a consequence, the expression of total impedance of the secondary circuit can be re-written in the form:

\[
Z_s = R_s + \frac{R_s}{1 + \omega^2 C_d^2 R_s^2} + j\omega_s \left( L_s - \frac{1}{\omega^2 C_s} - \frac{R_s^2 C_d}{1 + \omega^2 C_d^2 R_s^2} \right)
\]  (4)

In the above equations, the capacities of secondary side compensation capacitor can be selected in such a way that the imaginary part of \( Z_s \) equals zero. This means that the total impedance of the secondary circuit is purely resistive, the phase shift between secondary voltage and current, which supplies the piezoelectric actuator, is zero and no reactive power is drawn from the power. Hence the capacitor value for series compensation is as follows:

\[
C_s = \left( \omega^2 L_s - \frac{\omega^2 R_s^2 C_d}{1 + \omega^2 C_d^2 R_s^2} \right)^{-1}
\]  (5)

At the same time the final form of the expression of total impedance of the secondary circuit is:
\[ Z_s = R_s + \frac{R_e}{1 + \omega_s^2 C^2 R_e^2} \]  

So far, the equivalent circuit of whole ICPTs is as follows:

\[ (R_p + j\omega_s L_p)\hat{I}_p - j\omega_s M\hat{I}_s = \hat{U}_p \]  

\[ Z_r\hat{I}_s - j\omega_s M\hat{I}_p = 0 \]

The above equations are the basic loop equations of the primary and the secondary circuit. Reflected impedance, \( Z_r \), is introduced to reflect the impact that the secondary circuit exerts on the primary. The reflected impedance shows the transmission performance of system energy. The complex power absorbed by reflected impedance is just the one of secondary system. \( Z_r \) can be tentatively assumed as follows:
\[ Z_r = R_r + jX_r \]  

(9)

Where \( R_r \) and \( X_r \) are reflected resistance and reflected reactance respectively. Furthermore, the equivalent circuit seen from the primary side can be derived, as shown in Fig. 13.

The basic loop equations of the primary can be re-written as follows:

\[ (R_p + R_r + j(\omega L_p + X_r))I_p = U_p \]  

(10)

We can reduce (7), (8), and (10) to

\[ R_r = \frac{\omega^2 M^2}{Z_s} = \frac{\omega^2 M^2(1 + \omega^2 C_R^2 R_s^2)}{R_e + R_s(1 + \omega^2 C_R^2 R_e^2)} \]  

(11)

\[ X_r = 0 \]  

(12)

It can be seen that the imaginary part of \( Z_r \) equals zero, then the primary input impedance is purely resistive. The phase shift between input voltage and current is zero and no reactive power is drawn from the power amplifier. Summarizing, it may be concluded from the above equations that the secondary circuit impedance reflects to the primary side for purely resistive when the secondary circuit has been compensated for the purely resistive circuit. It is evident that primary reactive power is completely caused by self-induction of the primary winding. Therefore, the compensation of the primary circuit only offsets the primary self-inductance of the transformer, which produces reactive component. As to the rotatable transform, a concentrated primary winding often requires large primary currents; a parallel compensation plan is more attractive [28-30]. Hence a single capacitor at the terminals of the primary winding is used as shown in Fig. 14.
The expression of total impedance of the primary circuit with compensation is:

$$Z_p = \frac{(R_p + R_s)^3 + \omega^2 L_p^2 (R_p + R_s) - j \omega \left[ (R_p + R_s)^3 + \omega^2 L_p^2 \right] \left[ (R_p + R_s)^3 + \omega^2 L_p^2 \right] C_p - L_p}{(R_p + R_s)^3 + \omega^2 \left[ (R_p + R_s)^3 + \omega^2 L_p^2 \right] C_p - L_p}$$

(13)

In the above equations, the capacities of the primary side compensation capacitor can be selected in such a way that the imaginary part of $Z_p$ equals zero. This means that the total impedance of the primary circuit is purely resistive, and no reactive power is drawn from the power. Hence the capacitor value for parallel compensation is as follows:

$$C_p = \frac{L_p}{R_p^2 + \omega^2 L_p^2}$$

(14)
Finally, the total circuit model of the ICPTs with compensation can be drawn, and as shown in Fig. 15.

### 4 Turns Choice Criterion and Inductance Measuring Method

Based on the previous section analysis, the self-inductance of the secondary winding of the inner ring transformer ($L_s$) must be more than $R_c^2 C_d / (1 + \omega^2 C_d^2 R_c^2)$, according the real test in Section II (A), the following specifications are given: $C_d = 25nF$, $f_s = 67kHz$ and $R_c = 115\Omega$.

In this case, the self-inductance ($L_s$) must be more than 0.113 mH, and then an experimental prototype of the rotatable transformer has been developed with the following parameters. To simplify the analysis, the turn’s ratio of the inner ring transformer is set to 1, tentatively.

<table>
<thead>
<tr>
<th>Parameter (primary and secondary)</th>
<th>Inner ring transformer</th>
<th>Outer ring transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>turns</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Diameter of wire (mm)</td>
<td>0.35</td>
<td>0.5</td>
</tr>
</tbody>
</table>

In this paper, the self-inductance of primary or secondary of the rotatable transformer can be directly measured when the secondary or the primary circuit is opened, respectively. A series-coupling test approach is adopted to measure the mutual inductances. The advantage of the series-coupling measurements over the traditional measurement approaches is that there is no problem of the winding resistance discussed before. As demonstrated below, the inductances measured in the series-coupling tests are in the algebraic addition and subtraction of inductances and are independent of winding resistances and parallel paths, thus facilitating direct measurement by the LCR meter [33].

The transformer can be setup into two different series-coupling measurement configurations that the secondary connections are reversed compared to each other. One of configurations is series opposing, yielding the differential inductance ($L_{diff}$), as shown in Fig. 16(A). The simplified expressions of the $L_{diff}$, can be achieved as:

$$L_{diff} = L_p + L_s - 2M$$  (15)
In the cumulative measurement, as shown in Fig.16 (B), the cumulative inductance, \( L_{cum} \), can be determined using the same test setup, except that the secondary connections are reversed. The inductance is given by

\[
L_{cum} = L_p + L_s + 2M
\]  

(16)

According to (15) and (16), the general expression for the mutual inductance is given below:

\[
M = \frac{(L_{cum} - L_{diff})}{4}
\]

(17)

![Fig. 16: Mutual inductance test setup](image)

Equation (17) can be used to calculate \( M \) in the experimental section. In the case of different airgap distance, the measured data can be obtained, as shown by Tab 4 (LCR test frequency is fixed at 67 Hz).
Through the above measured data, it is found that there is deviation in the self-inductance between the first and secondary windings due to deviation in process. Because it keeps steadily over $19\pm1\mu H$ under different air gap, the deviation can be regarded as system error.

### 5 Experimental Evaluations of the ICPTs

To verify the real operation state of the ICPTs composed by the rotatable transformer, we established a set of experimental test bench, as below: Tektronix signal generator and RF power amplifier are used to construct the high-frequency AC power. Tektronix four ways oscilloscope is used as signal sampling device. The specific test parameters are stated here as the primary transformer is supplied by constant sine voltage power, voltage value of peak-peak is 100V with frequency of 67kHz, air gap of the rotatable transformer is setup to 2mm, $L_p=0.365646\text{mH}$, $L_s=0.347464\text{mH}$, $M=0.201250\text{mH}$, the sampling resistors of the first and secondary current are both $1\Omega$ of no-inductive precision resistors with power of 100W. The spindle speed is set for 3000 rpm, a slip ring installed on the rotor, is employed to deliver sampling signal from the rotating load (the balancing device) to stationary testing equipment's.

The first step is to do test without compensation in the inner transformer, and the equivalent test circuit is as following:

---

**Tab. 4** : Inductance measuring data for the rotatable transformer for different airgap distance

<table>
<thead>
<tr>
<th>Air-gap</th>
<th>$L_p$</th>
<th>$L_s$</th>
<th>$L_{cum}$</th>
<th>$L_{diff}$</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>396.308</td>
<td>376.632</td>
<td>1301.85</td>
<td>245.073</td>
<td>264.194</td>
</tr>
<tr>
<td>1</td>
<td>382.87</td>
<td>363.56</td>
<td>1223.27</td>
<td>270.804</td>
<td>238.116</td>
</tr>
<tr>
<td>1.5</td>
<td>373.811</td>
<td>355.193</td>
<td>1169.91</td>
<td>289.12</td>
<td>220.197</td>
</tr>
<tr>
<td>2</td>
<td>365.646</td>
<td>347.464</td>
<td>1116.03</td>
<td>311.03</td>
<td>201.250</td>
</tr>
<tr>
<td>2.5</td>
<td>359.313</td>
<td>341.567</td>
<td>1071.49</td>
<td>330.846</td>
<td>185.161</td>
</tr>
<tr>
<td>3</td>
<td>353.517</td>
<td>335.885</td>
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<td>321.42</td>
<td>880.584</td>
<td>438.835</td>
<td>110.437</td>
</tr>
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</table>
Fig. 17: Equivalent test circuit without compensation

Fig. 18: Waveforms captured without compensation
In fig.17, AC power stands for the high-frequency AC power, transformer $T_1$ represents the inner transformer of the rotatable transformer, the part in dash line stands for the real piezoelectricity actuator, and $R_{pm}$ and $R_{sm}$ signify the sampling resistors of the primary and secondary side current respectively. In this case, the waveform captured from Tektronix oscilloscope which shows the test of actual voltage and current waveforms are as Fig.18. (Channel 1 to 4 show respectively the output voltage of the high-frequency AC power, the output current of the high-frequency AC power, the load voltage of the real piezoelectricity actuator and the load current of load).

The second step is to add the primary and secondary compensative capacities simultaneously in the above picture according to the compensation theory in the above analysis, and the experimental circuit is as below:

![Equivalent test circuit after compensation](image)

**Fig. 19:** Equivalent test circuit after compensation
The parameter of compensative capacitors in the figure is calculated as the compensation theory as:

\[ C_p = 38.9 \text{nF}; \quad C_s = 1.75 \text{nF}. \]

Because of the good high frequency characteristic of ceramic capacitor, four ceramic capacitors of 10nF/2kV are used in parallel as the first compensative capacitor, and secondary compensative capacitors are two ceramic capacitors of 1nF/2kV. And the parameter of actual compensative capacitors is:

\[ C_p = 44 \text{nF}; \quad C_s = 2 \text{nF}. \]

Similarly, the waveforms captured from Tektronix oscilloscope which shows the test of actual voltage and current waveforms are as shown in Fig.20.

The third step is to observe the interference from the outer transformer to the inner transformer. To configure the practical circuit for the outer transformer ac-
According to the compensative circuit of the inner one, it is different to replace the internal resistance of unloaded driving power with a resistor of $R_{pl}$, as the following picture:

![Equivalent test circuit of the third step](image)

**Fig. 21:** Equivalent test circuit of the third step
The waveforms captured from Tektronix oscilloscope which show the test of actual voltage waveforms are as Fig. 22.

Experimental results drawn from the above experiments are as:

1. The rotatable transformer made of the self-made ferrite core can completely meet the requirements of the energy transfer and control of the dynamic balancing device.

2. Due to the application of the primary and secondary compensative circuit, operating at or near zero phase angle between the primary input voltage and the current is realized in the primary side circuit at first, and VA rating of the power amplifier can be reduced greatly, the result is that the peak-peak value of current of the supply power is reduced to 40mA from 100mA after compensation under the precondition that the first voltage keeps no change. Secondly, the reactive power of secondary circuit can be decreased greatly due to the presence of compensative capacitor. The peak-peak value of current of the load is reduced to 360mA from 700mA after compensation under the precondition that the driving voltage keeps no change.

Fig. 22: waveforms captured of the third step
Because the inner and outer ring transformers works alternately. It can be seen from Fig.22 that the inductive energy strength of the first and secondary windings of the outer ring transformer is very low (the inductive voltage of the primary winding is 140mV, and the one of secondary winding is less than 100mV) when the inner ring transformer is working. The dynamic balancing device driven by such energy cannot cause malfunction at all under such inductive energy strength.

6 Conclusion

This paper describes the implementation of ICPTs using a special stepwise contactless rotatable transformer to transfer high-frequency AC electric energy with power of about 10W to the balancing device which is mounted on rotor of the spindle and synchronous high-speed rotating with it. The rotatable transformer adopts special ferrite core material, which insures the machining accuracy and the whole strength of the transformer structure. This paper also makes detailed studies on the system models and compensation methods for the design and operation of the ICPTs operating at near zero phase angles between the primary input voltage and current at a locked frequency allowing maximum power transfer capability to be achieved. At last, contrast tests are applied to test the operation characteristic of the whole ICPTs under different operation state. The reliability of derivative result by theory is verified furthermore. By experiments, it is proved that this set of ICPTs can completely meet the requirements of the energy supply and control of the dynamic balance adjusting device.

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References


