Progress In Electromagnetics Research Letters, Vol. 20, 55–68, 2011

DEVELOPMENT OF LOW COST MEASUREMENT SYSTEM FOR RADIATED EMISSION EVALUATION

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Abstract—In this paper, a low cost measurement system with high accuracy for radiated emission evaluation has been proposed. By combining the test data of the current probe at different positions on the harness, the measurement accuracy is improved compared with conventional single probe method. For the sake of high accuracy, a transfer function is built to map the relationship between anechoic chamber method and current probe method. Based on experiments for evaluation, the final estimation of radiated emission agrees well with the measured results in anechoic chamber. For the cases tested, the difference between the current probe method and the anechoic chamber method is less than 3 dB.

1. INTRODUCTION

In the future, a more considerable portion of cost will be in automobile's electronic components [1–3]. The standard IEC/CISPR25 explains the measurement procedures [4]. According to this standard, the radio disturbance produced by the electronic components in a vehicle should be measured in the anechoic chamber to shield the noise from outside [5–8]. Figure 1(a) illustrates our specific implementation according to the general description in IEC/CISPR25. As the figure shows, the equipments consist of inverter, wire harness,

Received 19 October 2010, Accepted 27 December 2010, Scheduled 21 January 2011
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dummy load, receiving antenna and ground plane. All the circuit boards are packaged in the shielding boxes. As we know, it is highly expensive to build an anechoic chamber in a factory or school, and the test fee for the measurement is also high. Therefore, a low cost and efficient measurement method is expected while the accuracy can also be guaranteed. In order to solve the above problem, current measurement method by using current probe attracts much attention. The principle of current probe is near-field coupling. The detected signal is much more significant than the environment noise. Therefore, the measurement equipments do not have to be involved in anechoic chamber. If the accuracy can be satisfied by using this method in general laboratory, the cost could be reduced drastically. As shown in Figure 1(b), the current probe is located at the center of wire harness, and output port is connected with a spectrum analyzer. Due to the difference between the results obtained by the two methods, a transfer function mapping the relationship of the two results can be derived. Then the accuracy of estimation can be improved.

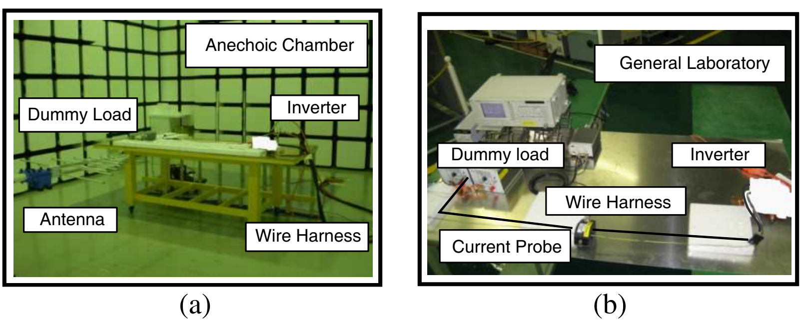


Figure 1. Measurement setup of anechoic chamber method and current probe method.

However, the current distributions on the wire harness are standing waves at some resonant frequencies. The amplitude of signal at the standing wave node is low. Thus, the measured results will be very sensitive to the location of current probe, which might result in error of the peak frequencies and levels in the measurement, then the estimation will be a large departure from the real data. In order to avoid this defect, a current probe method by combining multiple testing points of results has been proposed in this paper, and experimental results verifies the availability of this method.

2. PROPOSED METHOD

2.1. Analysis and Simulation of Current Distribution on the Harness

To overcome the shortcoming of single current probe, a low cost measurement method with higher accuracy is proposed in this study. Because the standing wave on the harness is steady, and does not change as time goes by. So in the actual experiment, we use only one current probe at multiple positions on the harness. One of the main tasks in this research is to determinate the locations of current probe and to combine these signals from different positions.

The mathematical expression for the standing wave on the harness could be supposed as follows:

$$E = ae^{+jkz+j\omega t} + be^{-jkz+j\omega t} \tag{1}$$

where a, b are arbitrary real number. Then the envelop of the standing wave could be denoted by

$$f(z) = \sqrt{(a+b)^2 \cos^2 kz + (a-b)^2 \sin^2 kz} \tag{2}$$

$k = \frac{2\pi}{\lambda}$ is the wave number. The wire harness is twisted-pair, which could be considered as a multiple conductor transmission line. So the wave on the harness is TEM mode. What is more, there is not any other dielectric around the harness. Therefore, we could approximately consider that the wavelength is the same as free space wavelength. z means the location on the harness as the following Figure 2 shows.

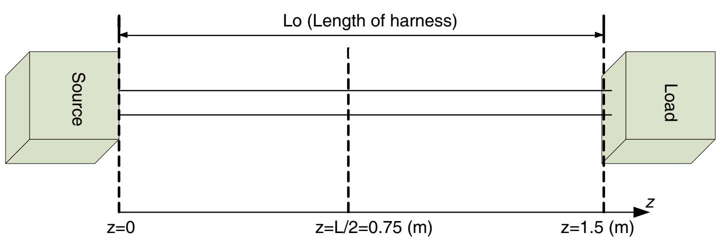


Figure 2. The coordinate built on the harness.

For example, the wavelength of 100 MHz standing wave is 3 m while the length of harness is fixed at 1.5 m. At the center point of the harness, $z = 1.5/2 = 0.75$ m. Then formula (2) $f(z) = |a - b|$ is minimum. The central point of the harness is the wave node. So in the spectrum, sensitivity of 100 MHz frequency point is low when the current probe is placed at the center.

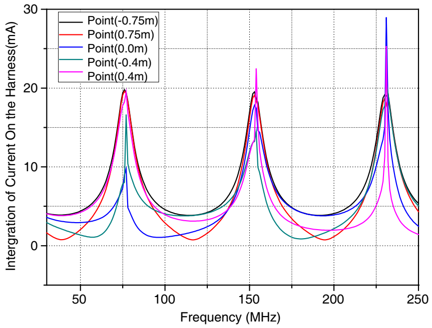


Figure 3. Peak frequencies on the frequency spectrum.

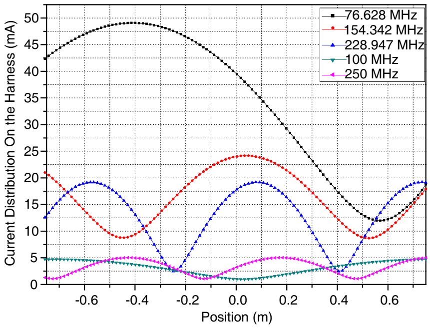


Figure 4. Simulation results of current distribution on the harness at different frequencies.

We do the simulation of current distribution on the harness in FEKO [9]. Frequency spectrum and the current distribution at different frequencies are illustrated in the following Figure 3 and Figure 4. Wire harness is driven by differential mode signal. As Figure 3 shows, there are three peak frequencies on the spectrum at five selected positions on the harness. The length of the harness is 1.5 m, and the point "(0.0) m" in Figure 4 is the center of the harness.

In Figure 4, the center of the harness is the wave node for the 100 MHz standing wave as the green curve shows. It is consistent with the mathematical analysis.

In Figure 3, the three peak frequencies are important to the study of radiated emission. The positions of the peaks should be covered by current probe. At the frequency 76.628 MHz, the wave length is longest. From the simulation results, the best position of current probe for 76.628 MHz wave is at -0.4 m point where is peak. But the peak level of 76.628 MHz is higher than other frequencies from Figure 4. Considering these aspects, we choose a comprising scheme. Three positions on the harness are selected as Figure 5 illustrates. The space of the three points is 10 cm. The shadow is the range covered by current probe.

To assure the accuracy, the max value from current probe at three positions is used for every frequency point. The scheme of current probe locations can eliminate the distortion of signal levels at peak frequencies.

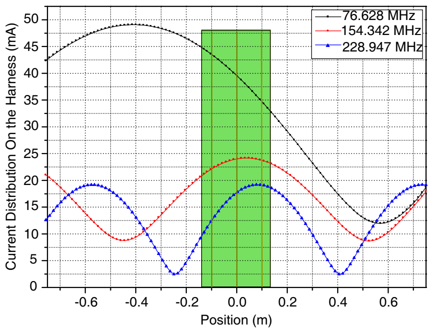


Figure 5. The measurement points on the harness.

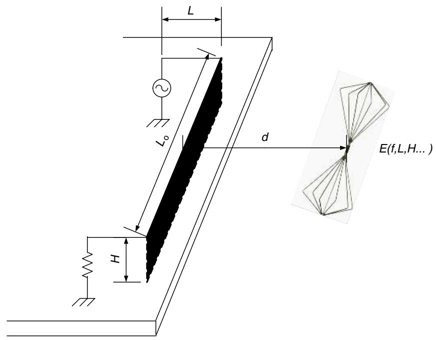


Figure 6. The basic theory of radiated emission.

2.2. Parametric and Sensitivity Study

Before the measurement, some parameters and their levels are supposed to have effect on the radiated emission peak levels and frequencies. By using Taguchi method, many combinations of the parameters are designed in the measurement. The results are used for parametric and sensitivity study. Our objective is to get a best combination of the parameters and to decide setup of measurement.

Figure 6 illustrates the basic theory of radiated emission. Common-mode current [10] on the harness and the ground plane constitute a current loop. Some parameters are supposed to have effect on the radiated electric field, such as length of harness L, height of harness over ground-plane H and some other parameters. A function $F(f, L, H \ldots)$ is used to represent the effect of these parameters. According to electromagnetic theory, the intensity of radiated electric field can be denoted by a formula as follows:

$$E(f, L, H, d \ldots) = L_O H f^2 F(f, L, H \ldots) I(f)/g(d) \tag{3}$$

$L_O \times H$ is the area of radiation which can be seen from Figure 6. f means frequency of signal, and d is the distance between harness and antenna. $g(d)$ is a function of distance which is dependent on whether the receiving antenna is in near field or far field. $I(f)$ represents the current on the harness. $I(f)$ can be denoted by characteristic of current probe $K(f)\,(A/V)$ and the results of measurement by current probe $M(f, L, H, \theta, g)\,(V)$:

$$I(f) = K(f) \times M(f) \tag{4}$$

So the formula (3) can be denoted by another form:

$$\begin{aligned} E(f, L, H \ldots) &= L_O H f^2 F(f, L, H \ldots) K(f) M(f, L, H \ldots)/g(d) \\ &= L_O H f^2 F(f, L, H \ldots) K(f)/g(d) \times M(f, L, H \ldots) \end{aligned} \quad (5)$$

Parameters and measurement results in formula (5) are divided, and transfer function is used to denote the parameters. Then there are two equations as follows:

$$E(f, L, H \ldots) = T_r(f, L, H \ldots) M(f, L, H \ldots) \quad (6)$$

$$T_r(f, L, H \ldots) = E(f, L, H \ldots)/M(f, L, H \ldots) \quad (7)$$

Based on the above theory analysis, four parameters are supposed to have effects on the voltage at antenna feed port. They are L (length of harness connecting signal source to load), H (harness height over ground plane), g (gap between harness and supporter) and θ (bent angle of harness) [11]. The details of the four parameters are illustrated in Figure 7.

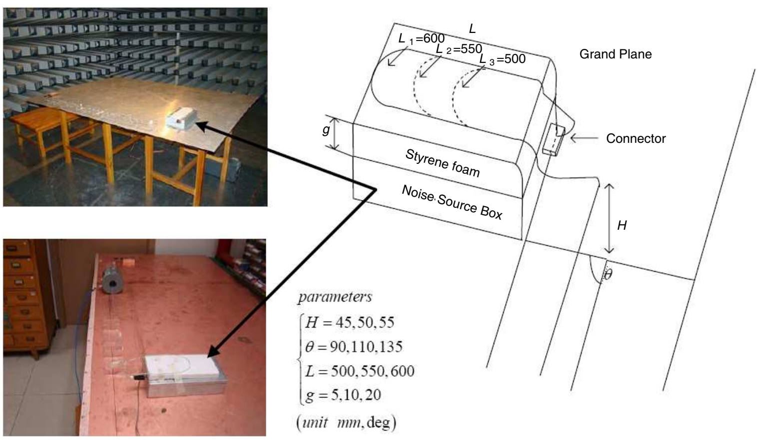


Figure 7. The detail of parameters.

In order to choose the best combination of parameters, parametric study should be done in detail. In this study, the sensitivity of four parameters will be tested and analyzed.

There are four parameters, and three levels for each parameter are chosen. L: (600, 550, 500), H: (55, 50, 45), θ: (90, 110, 135), g: (20, 10, 5) [11] as shown in Figure 7. The dimension for L, H, g is mm and that for θ is degree.

By conventional method, the total number of experiments for parametric study should be $3^4 = 81$. The workload is too heavy and complex to finish. Therefore, before the measurement, another approach should be found to redesign the experiments. The objective is to reduce the number of measurements drastically without information lost. Taguchi method could meet the requirements [12].

The main work of Taguchi method is to design a set of arrays which are orthogonal. Then the following experiments will be carried out based on the set of arrays [13].

The general steps are as follows:

1) Determine the parameters which are to be studied. The number of parameters is denoted by p.
2) Determine the levels of each parameter, whose number is denoted by s.
3) Design the orthogonal arrays.
4) Do the experiment according to the set of arrays.
5) Analyze the results [11–13].

The set of orthogonal arrays is denoted by $L_n(s^p)$. L represents the orthogonal table. s and p are explained in step 1) and 2) respectively. n is the number of the orthogonal table rows. which is also called the number of the experiments. Based on determined s and p, n can be got according to orthogonal arrays of Taguchi method.

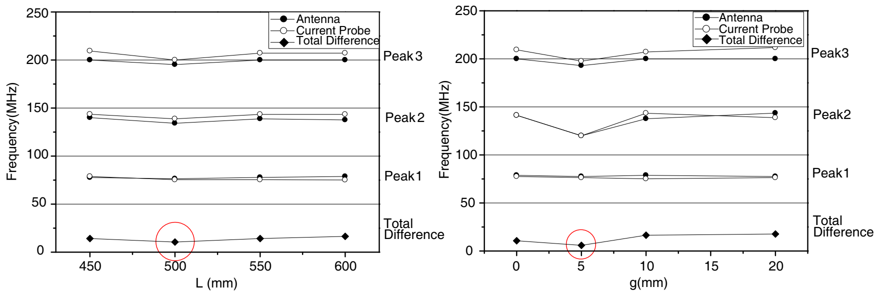
For example, $p = 4$ and $s = 3$. If we use Taguchi method, the number of experiments will be reduced to 9. The orthogonal table is denoted by $L_9\,(3^4)$. The four parameters are independent. Arbitrary two columns in the table are orthogonal. The order should not be changed. Each row is a specific combination. The information involved in the table is dispersed equally, which are equal to the whole information of 81 sets of data [11–13]. Table 1 shows the experimental cases for parametric study.

Table 1. Exeperimental cases for parametric study.

No.	L (mm)	H (mm)	θ (deg)	g (mm)
1	600	45	135	5
2	600	50	110	10
3	600	55	90	20
4	550	45	90	10
5	550	50	135	20
6	550	55	110	5
7	500	45	110	20
8	500	50	90	5
9	500	55	135	10

When results are got after the measurement is finished by Taguchi method, the sensitivity analysis has to be done to select the best combination of the four parameters.

Each of these parameter sets for the current and the antenna port voltage was measured. The criterion of selection for the level of each parameter is the difference between method of anechoic chamber and method of current probe which can be denoted by sensitivity. The selection of $H = 50\,\text{mm}$, $\theta = 90\,\text{deg}$ is decided by general standard. The effect of L and g is larger than H and θ. Therefore, further analysis of parameters L and g should be done. Another level is added to each parameter, L: (600, 550, 600, 450) mm and g: (20, 10, 5, 0) mm while H and θ are fixed (50 mm, 90 deg). The following Figure 8 shows the sensitivity curves between the method of anechoic chamber and that of current probe at different peaks. When the difference of peak frequencies between anechoic chamber and general laboratory is smallest, the result agreement of the two methods is best.



(a) (b)

Figure 8. Sensitivity analysis of L and g. (a) The sensitivity analysis of L. (b) The sensitivity analysis of g.

From the results of sensitivity analysis, the best combination of the four parameters can be determined: $L = 500\,\text{mm}$, $g = 5\,\text{mm}$, $H = 50\,\text{mm}$, $\theta = 90\,\text{deg}$.

2.3. Transfer Function by Combining Antenna in Anechoic Chamber and Current Probe in Laboratory

After the parametric study, a best combination of the parameters has been chosen. Then this combination condition is used as the common setups. Transfer function under this condition mapping the results of current probe and that of anechoic chamber will be derived and analyzed carefully. Then the accurate radiated emission can be reappeared only by the current probe.

Based on the above analysis, we have demonstrated that there is a transfer function between the current and antenna port voltage in theory. When the combination of parameters is determined, the transfer function will be derived under this condition. The transfer function is got by polynomial interpolation. Peaks in the spectrum are important to radiated emission. The peak points are chosen to do the interpolation.

It can be seen in Figure 9 that the three peak frequencies and levels are selected. The three peaks are used for deriving the transfer function. The raw data for transfer function are the differences between peak values.

The following Table 2 is the data for getting transfer function. Raw data which are the differences between the antenna and current probe at peak frequencies are used to do interpolation in MATLAB. Then the transfer function denoted by a poly formula is got.

The formula of transfer function is

$$y = a_6 x^6 + a_5 x^5 + a_4 x^4 + a_3 x^3 + a_2 x^2 + a_1 x + a_0 \tag{8}$$

Item	a_1	a_2	a_3	a_4	a_5	a_6
Value	$1.32-e13$	$-2.91-e10$	$2.24-e7$	$-7.64-e5$	$-5.67-e1$	$-1.68+e1$

The curve of transfer function is as the following Figure 10 shows.

3. RESULTS AND VERIFICATIONS

The source circuit in our measurement includes DC-DC power supply, FPGA chipset and USB interface. We can use FPGA as a code generator to output periodical waveforms, and the USB interface will

Table 2. Data for getting transfer function.

L	H	theta	g
500	50	90	5
	Freq (MHz)	Raw data	
	30.00000	−25.00000	
	77.70000	−20.0000	
	138.00000	−18.0000	
	202.35000	10.0000	
	269.40000	−37.0000	

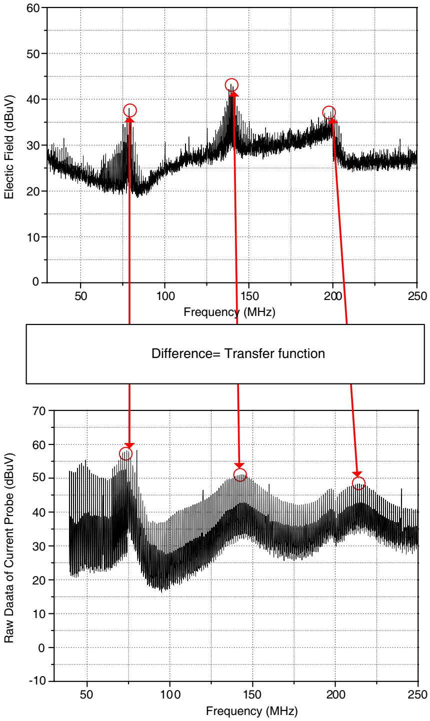


Figure 9. The three peaks for transfer function.

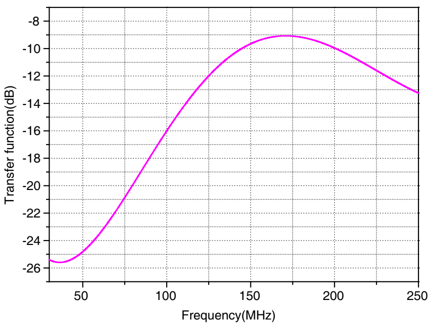


Figure 10. The curve of transfer function.

guarantee the required transmission data rate. The model of source for the anechoic method and current probe method is the same.

The frequency in our measurement is from 30 MHz to 250 MHz, so in the anechoic measurement, we choose two types of antennas: 1) 30 MHz to 200 MHz, a biconical antenna, 2) 200 MHz to 250 MHz, a log-periodic antenna. The phase centre of the measuring antenna is $(100 + 10)$ mm above the ground plane while the distance between the wire harness and the reference point of the antenna is (1000 ± 10) mm.

The bandwidth of current probe in the measurement is from 10 KHz to 400 MHz, and t the input power rating is 100 watts.

The measurement set-ups are as Figure 7 shown. When the preparing work has been finished, the measurement is carried out. The procedures are as follows:

a) In anechoic chamber:
   1) Set up the measurement equipments and position the antenna at proper locations.
   2) Download the program to FPGA to generate the signal.
   3) Measure the radiated emission from wire harness by antenna.

b) In general laboratory:
   1) Set up the measurement facilities which should be the same as in the anechoic chamber, and locate the current probe at fixed position which is based on the above analysis.
   2) Download the program to FPGA to generate the signal.
   3) By using spectrum analyzer, we get the data for current probe method.

c) Get the transfer function based on the above method.

d) Do the verifications to check the proposed method.

We do two verifications. In the first test, the frequency of signal is 660 KHz. The estimation values of radiated emission can be got by the following formula:

$$Estimation = Transfer + S_{probe} \tag{9}$$

The comparison between the values of estimation and the measurement results of antenna in the anechoic chamber is shown in Figure 11. From Figure 11 we can see the largest disagreement between peak levels is 1.25 dB and shift of peak frequencies is 3%. The accuracy of estimation is satisfying.

This is a linear system, so formula (9) should be valid for every frequency. In Figure 11, the yellow curve is background noise in anechoic chamber which cuts the low values. Therefore, the shapes of the two methods around the peaks are not the same. The accuracy depends on the transfer function which is just effective in the situation where it is derived. In another words, the signal source should be the same. However, we don't know whether the transfer function also can be useful in other situations.

Figure 12 shows the second verification. The frequency of signal is doubled and the same work as Figure 11 is done. The same transfer

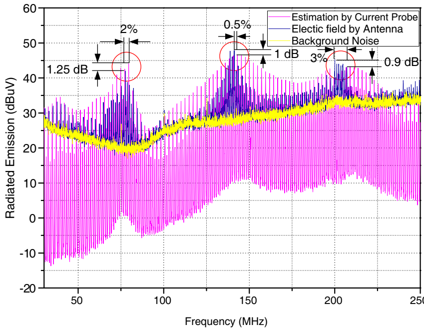


Figure 11. Comparison of two methods for original signal.

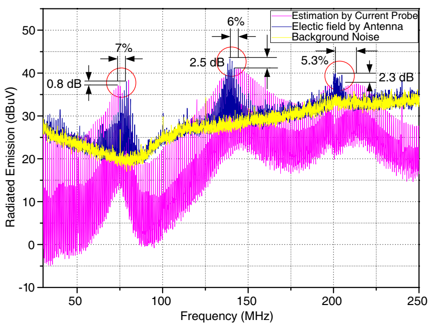


Figure 12. Comparison of two methods for another signal.

function got in Figure 11 is also used. Then based on formula (9), the estimation values of radiated emission are got when signal has been changed. The comparison between the real accurate values in the anechoic chamber and the estimations is pictured in Figure 12. The largest disagreement of peak values is 2.5 dB which satisfies the general engineering target ±3 dB. The largest peak frequency shift is 7% that is also acceptable.

4. CONCLUSIONS

In this paper, a novel method for estimating the radiated emission has been presented. Innovation of our study is to locate current probe at multiple positions. Accuracy of estimation then could be improved. To decide the locations effectively, simulation of current distribution on the harness is done to describe the effect of standing wave. By using Taguchi method, workload of measurement is reduced greatly. Then from sensitivity analysis, a best combination of parameters is obtained. Under the specified situation, a transfer function is derived to map the results of antenna in anechoic chamber and current probe in laboratory. A good agreement is achieved between the estimation and the anechoic chamber method. Then the contradiction between accuracy and low cost has been solved [11]. However, there are also limitations in this method. The method works well from 30 MHz to 250 MHz. In the future, further work has to be done when frequency is increased. In addition, although the transfer function is applicable when the frequency of signal is doubled, its applicability in other situations is a subject of future study. Maybe a lot of work has to be done to get a completely satisfying conclusion.

ACKNOWLEDGMENT

The authors wish to acknowledge the teachers in Beijing Jiaotong University and the 15th institute for the support in the anechoic chamber measurement, the National institute of Metrology P. R. China for providing current probe. This work was supported by the National Basic Research Program of China under Contract 2007CB310605, by the National High Technology Research and Development Program of China (863 Program) under Contract 2009AA011503, by the National Natural Science Foundation of China under Contract 60771009, and by Mitsubishi Heavy Industries, Ltd.

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