Abstract—The crosstalk coupling for wiring harness in vehicle has great influence on electromagnetic compatibility (EMC), it is necessary to estimate it at the beginning of EMC design of system. The relative position between wires in harness is random, the deterministic methods based on constant harness geometry are inappropriate to estimate crosstalk, while the statistical methods can reflect the actual crosstalk coupling, reveal random nature of crosstalk. The paper described three kinds of statistical models of crosstalk, and each model has its own characteristic and scope of application: the worst case method is appropriate to find potential crosstalk quickly, both probabilistic model and segmentation method catch the quantitative statistical characteristics of crosstalk i.e. mean value and standard deviation, the segmentation method can estimate the crosstalk in non-uniform wiring harness particularly.

Keywords-electromagnetic compatibility; crosstalk; vehicle; statistical estimation; wiring harness

I. INTRODUCTION

With vehicle safety, comfort and increased control development, more and more electrical equipments were installed in the vehicle, and the emergence of X-by-wire or drive-by-wire accelerated the trend. The increased number of electrical equipments led to an increased amount of wiring harness in the vehicle. The wiring harnesses are routed tightly together, and the chassis is often used as a ground return path. All wires are collected into thick bundles that are routed through the vehicle. A potential problem with these harnesses is the presence of crosstalk. Crosstalk is unintended electromagnetic coupling between wires that are in close proximity. This unwanted signal may increase the noise levels, create unplanned spikes and jitter on data edges. There were also cases where crosstalk could affect the radiated and/or conducted emissions of the system [1]. In a word, the automotive electromagnetic compatibility (EMC) can be a strong decline due to crosstalk. Crosstalk should always be a prime target in an Electromagnetic Interference (EMI) investigation.

In recent decades, crosstalk has been extensively investigated and many estimation models have been developed for a wide variety of wiring structures [2], such as full-wave model [3], circuit simulation model based on the transmission lines [4], and so on. The majority of these models assume that all the geometrical parameters of the wires in harness, i.e. the relative position of wires within a harness, the height of the wires from the ground, are deterministically known, whereas such an assumption does not conform to the fact. As the vehicle movement, hand-assembled wiring harness and other reasons, the geometrical configuration of the wires in the bundle varied, so above deterministic approaches are not suitable for crosstalk estimation for wires in vehicle; we must use statistical methods to deal with the randomness of crosstalk for wires in vehicle.

II. CROSSTALK ESTIMATION

There are two steps to estimate the crosstalk, the first step is to determine the per-unit-length (p.u.l) parameters of wiring harness, i.e. self and mutual inductances and capacitances; the second step is to solve the multi-conductor transmission lines (MTL) equations through p.u.l parameters.

The p.u.l parameters can be determined by solving Maxwell’s equations and Laplace's equation with relevant boundary conditions and initial conditions in combination with image method [1]. More suitable technique is computational electromagnetics. Reference [5] used the Finite element method (FEE), reference [1] used the method of moments (MOM), and reference [6] used the Finite-difference time-domain (FDTD). In recent years partial element equivalent circuit (PEEC) has been used to compute the p.u.l parameters widely [7]. There are several other hybrid methods.

When the parameters are determined, the crosstalk can be estimated by solving the MTL equations. The approximate methods are the inductive-capacitive coupling model, lumped-circuit approximate model including lumped $\pi$ and lumped $T$ etc., and the exact solutions are circuit simulator software consisting of SPICE/PSPIE and Saber and so on.

Crosstalk estimation need to determine the p.u.l parameters of wires, and the p.u.l parameters relate to geometrical parameters (the relative position of wires in the bundle, the height of the wires from the ground, etc.) and electrical parameters( loads, media, etc.) of the wires in the bundle. When the geometric parameters and electrical parameters of wires change, the p.u.l parameters of wires will change accordingly. As the vehicle movement, hand-assembled wiring harness and other reasons, the geometrical configuration of the wires in the bundle is varied, wire positions along the bundle, winding degree and the height from the ground are unknown, undetermined and uncontrolled, and so the p.u.l parameters varied too. If the crosstalk is estimated according to the deterministic geometrical configuration, the value is error. The paper...
studied three types of statistical methods to estimate the crosstalk in vehicle wiring harness to deal with the undetermined p.u.l parameters.

III. STATISTICAL ESTIMATION OF CROSSTALK

Reference [8] experimentally investigated the variation of a cable crosstalk due to the random positions of wires in the bundle, and the range of variations was larger than 20 dB. They also found the crosstalk sensitivity was the function of the terminal loads. They used the tolerance interval approach to estimate the crosstalk. Reference [9] developed numerical techniques for the statistical estimation of crosstalk. These numerical models were based on quasirandom fluctuations of the line conductors in the bundle cross section, and repeated-run analysis were used for model validation against experimental measurements.

At present, the statistical methods are main approaches to estimate the crosstalk of wires in vehicle harness, and the methods consist of the worst case method, probabilistic model method and the segmentation method, and so on.

A. Worst Case Method

The crosstalk can be determined if the mutual induction \( l_m \) and mutual capacitance \( c_m \) are known, and the determination of the mutual induction and mutual capacitance need to know the distance between the wires in the bundle. The distances vary within a certain range randomly. When the distance is a particular value, the crosstalk is the maximum (a worst case). Daryl G. Beetner et al. found that the worst-case algorithms performed well up to 10-20 MHz through the experiments, but overestimated results by several dB in some cases and up to 10-15 dB in others [10].

Fig.1 showed the comparison measured with estimated crosstalk among circuits with separate or shared return wires when capacitive coupling dominates, and the crosstalk under the worst case overestimated indeed in Fig.1. The reason for overestimated crosstalk was that the worst case could never actually occur or could only occur in a very few instances. It required the people to prove or refute the seriousness of those problems. Daryl G. Beetner et al. modified the worst case algorithms and proposed the reasonable worst case algorithms which introduced the statistical method [10].

The modified method may exclude cases that would only rarely occur and report reasonable case. Statistical estimates of crosstalk were made using Monte Carlo methods. Fig. 2 showed measured and estimated values of crosstalk using worst case and Monte Carlo methods. Measured values of crosstalk were near to the estimated crosstalk and within the 80% confidence interval. Below 4 MHz, the worst case estimate of crosstalk was generally about 3 dB higher than the 80% confidence interval and generally about 6 dB higher than the measured crosstalk.

The worst case method was used to an expert system for automotive EMC problems initially [11]. The method can rapidly find the potential crosstalk problems during the early design with incomplete system information. While the results do not give precise levels of crosstalk, they will reveal specific problem areas and allow the user to focus their attention on these problems. Though the worst case method takes the risk of overestimated crosstalk, it better ensure that problems will not be missed, especially in the absence of complete system information. The most important feature of this approximation method is fast computation.

B. Probabilistic Model Method

Shabtay Shiran et al. proposed a probabilistic model of crosstalk [12]. The canonical deterministic model of crosstalk was translated to probabilistic terms by assuming a rectangular uncertainty region for the wires in the line’s cross section. An analytically implicit expression of the crosstalk probability density function (pdf) and cumulative distribution function (cdf) were derived. The method based on a three-conductor uniform and lossless transmission line with resistive loads.
Fig. 3 illustrated the location of each wire was determined by a pair of independent random variables: its height above the ground plane and its horizontal distance from the origin, \( 0 \leq d_R, d_G \leq d \), \( h_{\text{min}} \leq h_R, h_G \leq h_{\text{max}} \), \( d_R, d_G, h_R, h_G \) were random variables uniformly distributed. So a rectangular uncertainty region was set up on the cross section of wires. The pdf of \( d_R, d_G \), i.e. \( f_{d_R}(d_R) \), \( f_{d_G}(d_G) \) could be derived, and the pdf and cdf of horizontal separation of two parallel wires, \( d = d_G - d_R \), i.e. \( f_d(d) \), \( F_d(d) \) could be derived, according to the joint pdf. The pdf of mutual induction \( l_m \) and mutual capacitance \( c_m \) could be derived according to the definition of induction and capacitance coupling. Finally, an analytically implicit expression of the crosstalk pdf and cdf was derived. The analytic result of cdf was compared with the simulation result, as shown in Fig.4, it can be seen they were close together.

The above probabilistic model was limited to electrically short transmission lines. An extension of this model was developed by D. Bellan etc., in which the receptor circuit embedded all the interference effects due to the presence of the generator circuit. Such effects were represented by a noise and a current lumped noise sources and a distributed-parameter passive two-port. Under the weak-coupling and matched generator circuit assumption, the closed-form expressions of near-end (NEXT) and far-end (FEXT) crosstalk voltage transfer ratios which reflected the randomness of relative position of wires, and mean value and variance of crosstalk were derived.

The difference with Shabtai Shiran was that D. Bellan introduced an uncertainty region with circular sector to determine the relative position of wires, as shown in Fig.5. Assuming that the receptor wire had radius \( r_{wR} \), and it was located at a given height \( h_R \) above the ground plane, the generator wire had radius \( r_{wG} \) and it was located in a random position described by the geometrical parameters \( s \) and \( \theta \) which were used for tracking random fluctuations of generator wire G around receptor wire R, in the uncertainty region, treated as independent random variables (RVs), distributed within the intervals \( s \in [s_{\text{min}}, s_{\text{max}}] \) and \( \theta \in [\theta_{\text{min}}, \theta_{\text{max}}] \). Hence, for limited-amplitude fluctuations of the generator wire, the mean value and the variance of NEXT and FEXT can be expressed in terms of the statistical properties of \( s \) and \( \theta \) by resorting to a Taylor series approach. The analytical expressions of mean value and standard deviation of NEXT compared with numerical simulations, and good agreement between numerical and analytical results was achieved, as shown in Fig.6.

The probabilistic model method not only obtains general statistical form of crosstalk, i.e. probability density function and cumulative distribution function, but also catches the most relevant statistical characteristics of crosstalk, i.e. mean value and standard deviation. It quantifies the statistical characteristics of crosstalk.

C. Segmentation method

The worst case method and probability model method both model the overall wiring harness, which F. G. Canavero etc. developed a cascaded circuit model, which represented the overall harness as a distributed multi-port device with
random parameters [9]. The segmentation method not only models the uniform wiring harness, but also models the non-uniform wiring harness especially.

Diego Bellan and Sergio A. Pignari developed an estimation model to crosstalk in non-uniform wire bundles with resistive loads [14]. In order to include the non-uniformity of cable in the model, they assumed a constant geometry of the cross-section, and a location of the generator and receptor wires within the cross-section that changes over the longitudinal coordinate. The cable, therefore, can be modeled as a cascade of $N_s$ sections of uniform transmission lines. The larger the number of sections $N_s$, the stronger the degree of non-uniformity which the model can describe. Each section is $\Delta l_k$ in length, with $k = 1, \ldots, N_s$, under the constraint $\sum_{k=1}^{N_s} \Delta l_k = \ell$, $\ell$ is the length of the wire.

Under the assumptions of electrically short and weakly coupled transmission line, the analytical mean value and standard deviation of the near-end crosstalk voltage ratio were derived. The formula includes the number of section, the mean value and the standard deviation of the mutual inductance and mutual capacitance in section, reflect the bundle non-uniformity. The analytical result compared with the simulation result, the agreement is good, as showed in Fig. 7.

Meilin Wu etc. divided the wiring harness into several segments to deal with the problem of twisted wires which caused the position of the wires to change along the length of the harness [15]. Wires are assumed to remain in the same positions along each segment of the harness and to take on new positions in adjoining sections. Assuming the distribution of positions was uniform and independent between segments and that segments were of equal length, the collective distribution of mutual inductance and capacitance were convolution of the distributions for each segment.

Shishuang Sun etc. also divided the non-uniform random bundles into $n$-cascaded segments of a uniform multi-conductor transmission line to deal with the random disturbance of the wire positions along hand-assembled cable bundles [16]. At each section, all wire positions obeyed a Gaussian distribution. The method Shishuang Sun etc proposed was different from Diego Bellan’s, though based on the segmentation method. Sun’s were more concern about the continuity between adjacent segments. Prior to this, S. Salio and F. Canavero etc. proposed the random midpoint displacement (RMD) algorithm to deal with the discontinuity between the segments [17]. The algorithm described the positions of a wire along a bundle with a fractal curve. The continuity of the wires within cable bundles was controlled through the fractal dimension and the total number of segments. The RMD method gave a better representation of an actual wiring harness in continuity and randomness. However, because of the nature of the algorithms, the constructed wires with RMD method resulted in unphysical large discontinuities between adjacent bundle segments. The large discontinuities resulted in unphysical resonances of the common mode (CM) current along cable bundles, which decreased the effectiveness of models, especially at high frequency. Shishuang Sun etc. proposed a new method, i.e., the random displacement spline interpolation (RDSI) algorithm, which introduced the random numbers obeying the Gauss distribution into the wire position and a spline interpolation function to improve the continuity between adjacent bundle segments. Fig.8 showed three-dimensional visualization of two wires within a 14-wire bundle constructed with the RDSI and RMD algorithms. The wires constructed with the RDSI algorithm demonstrated a better continuity than RMD algorithm from the Fig.8.

Though modeling the random bundles as $n$-cascaded segments of a uniform multi-conductor transmission line, Diego Bellan, Meilin Wu, and Shishuang Sun approaches are still different. Diego Bellan and Meilin Wu estimate the NEXT directly after divide the bundles into segments, however, Shishuang Sun take the note of the transition of the segments. At each section, Meilin Wu assume all wire positions obeyed a uniform distribution, which Shishuang Sun assume it obey Gaussian distribution.

![Figure 7](image-url) Standard deviation of NEXT: analytical versus numerical results

![Figure 8](image-url) Three-dimensional visualization of two wires
There are other statistical estimations of crosstalk in wiring harness. Monte Carlo method is a classical approach, and used to estimate the crosstalk in many articles or compare other methods rely on it[18]. In addition, there are neural networks[19], wavelet theory [20], and so on.

IV. CONCLUSION

Crosstalk between wires in vehicle harness affects Electromagnetic compatibility (EMC) severely and it should be estimated in the product design stage. As the geometrical configuration of the wires in vehicle wiring harness is random, the errors of the deterministic methods of crosstalk are large; the statistical methods are appropriate approaches.

The paper studied three types of statistical estimations of crosstalk in vehicle wiring harness, and the result shows each method has its own application of the occasion. The worst case method fits for initial design phase in which little information can be gain and it can find potential crosstalk quickly. The risk of the method is probable overestimate, but it can be amended through Monte Carlo method. Both probabilistic model and segmentation method can get the most significant statistical characteristics i.e. mean value and standard deviation, which quantify statistical characteristics of crosstalk. The segmentation method applies to estimation of crosstalk in non-uniform wiring harness particularly.

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