

High Speed Data Across Sliding Electrical Contacts

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ABSTRACT—The transmission of high speed data has become increasingly important in systems that utilize slip rings for the transmission of data from rotating to stationary platforms. Traditional evaluation metrics for the suitability of sliding contacts to carry signals or data have evolved from the D.C. and analog world and do not accurately predict performance with high speed data. Contact “noise”, or variation in contact resistance, is universally used to evaluate contact quality, but this standard method requires extensive re-definition and augmentation to accurately predict the efficacy of a high data speed sliding contact system. This paper presents both experimental and analytical data to show the critical characteristics of a sliding contact system that can transmit digital data up to 3 gigabits per second (Gbps). Digital data signal characteristics are reviewed and compared with the features of sliding electrical contacts to identify the potential areas of concern. Data is presented to show performance of a sliding contact system designed expressly for the transmission of high speed data. The influences of micro and macro contact environments are examined and key tribological factors are reviewed.

I. INTRODUCTION

The study of sliding electrical contacts has traditionally been divided into two areas of study: power capacity and signal quality. The study of power contacts is typically focused on an understanding of the impact on the contact from power loading and the effect power (both current and voltage) have on the power rating and contact reliability. On the other hand, the study of sliding electrical contacts used for signal transfer is focused on the ability of the electrical contact to function within a signal transmission line with minimal impact on signal quality. It is on this area of signal quality of sliding electrical contacts that this paper will focus, specifically on the transmission of high speed data.

For the past 50 years the critical parameter of signal quality has been the variation in contact resistance experienced by electrical contacts while sliding [1, 2]. This variation in contact resistance produces signal noise as resultant voltage and/or current perturbations governed by ohms law. These changes in contact resistance with sliding are dependent upon a number of key parameters including surface film changes [3, 4], physical parameters such as contact force, sliding speed, surface roughness, vibration [2, 5-8], or particulate contamination from wear debris or outside sources [1, 9]. This activity occurs on the micro-level, i.e. in the zone where the two elements of the electrical contacts actually have their interface.

Early researchers [10, 11] described the mechanics of electrical contact as multiple micro-asperities in contact. Electrical contact resistance resulting from a low number of contact points and low contact area constricts the electron flow

near the asperities actually in contact [12]. This resistance is commonly called constriction resistance. Constriction resistance is defined as the increase in resistance due to the replacement of a perfectly-conducting interface by a constriction [13]. This model is shown in Figure 1. Much of the work on electrical contacts in the past 20 years has been focused on describing and modeling the contact asperities and their contact resistance using sophisticated numerical techniques [14-17].

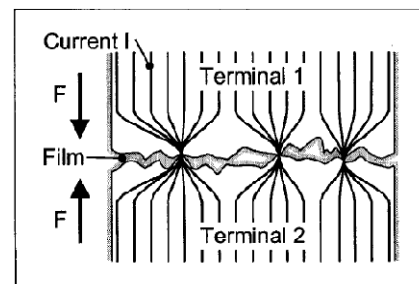


Figure 1. Contact zone showing contact points and film in the gaps

The theoretical model developed by Antler [1] is still commonly cited as the explanation of sliding contact resistance variation phenomena. In situations of a metal rider on a metal ring, severely-worked metal from the ring transfer to the rider forming a prow-shaped wedge which adheres to the rider. Even when rider and ring are different material, the prow material is transferred from the ring. Loss of the prow from the rider occurs by adhesive weld-back transfer and, to form loose debris, by shearing or fatigue fracture. Contact resistance noise originates in stick-slip, wear debris generation, and surface hardening. Figure 2 (from [18]) illustrates this prow formation. A more recent study provides a discussion of the effect on noise of normal force, surface roughness, initial run-in, sliding speed, and liquid lubricants [2] and [19] provides a study of the relationship of contact sliding speed to the frequency spectrum of the noise, or resistance variation.

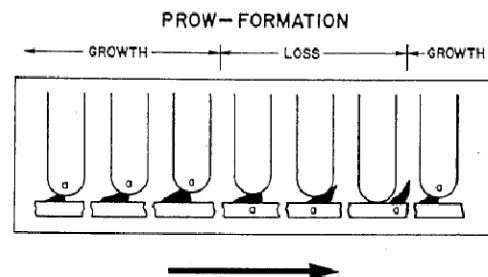


Figure 2. Prow formation on rider of sliding electrical contact (from Ref 18)

The variation in contact resistance, or contact noise, is the figure of merit that has been used over the years to evaluate the suitability of sliding contacts to transmit analog and low speed digital data. As the use of sliding electrical contacts for the transmission of digital data continues to proliferate, investigations are overdue on the critical parameters of sliding electrical contacts in the transmission of high speed data. Are there other figures of merit besides contact noise that should be considered when high speed digital data is being transmitted?

II. CRITICAL PARAMETERS

As we discuss high data rates, the most important issue to consider is the frequency components of all digital signals, as shown in Figure 3. In order to transmit high data rate signals with reasonable bit error rates (BER), a transmission line must be capable of handling at least the 3rd and ideally the 5th harmonic of the fundamental frequency (the fundamental sine wave frequency is typically one-half of the bit rate). This frequency capability of the transmission line is called its bandwidth. So a transmission line with a bandwidth of 1 Ghz could be expected to carry a digital signal with a bit rate of 400 Mbit/sec (400 Mbps x 0.5 MHz/Mbps x 5) with good fidelity. This is a frequency domain evaluation of a digital pulse.

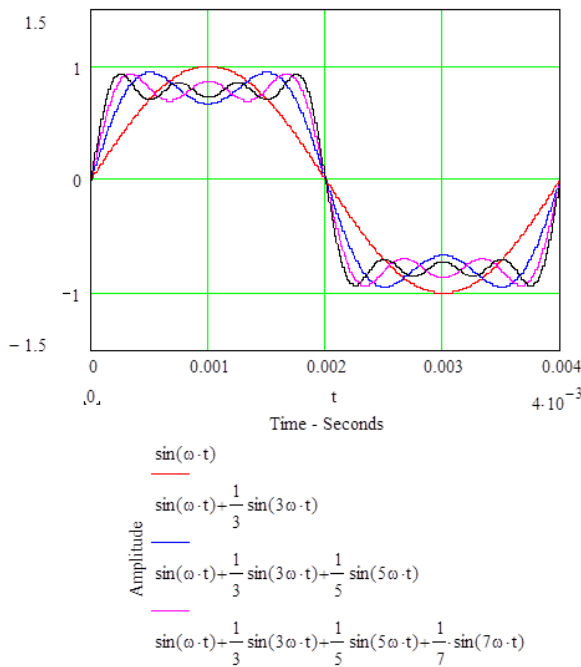
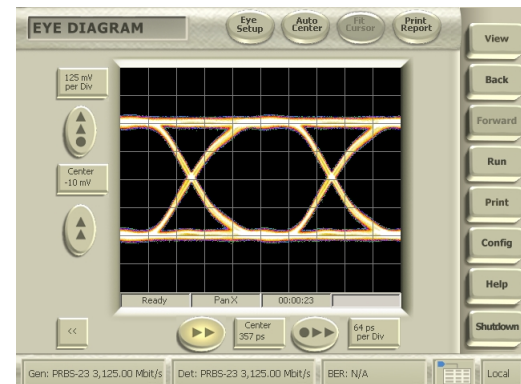


Figure 3. Frequency components of a square wave

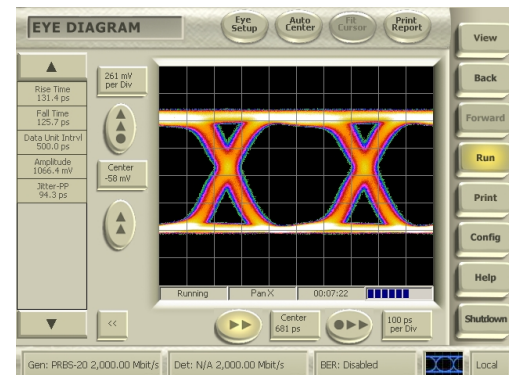
In the digital world the quality of digital transmission is normally evaluated in the time domain. Eye diagrams are used to indicate in the time domain the predicted BER of transmission lines. Eye diagrams are formed by capturing a digital signal and “laying” bits of the data stream on top of each other. If there is no phase delay from poor transmission line quality, the square waves should align exactly. When the higher frequency components of the square wave are transmitted effectively, an eye diagram similar to the one shown in Figure 4 (a) is produced. When the transmission line

produces phase delays due to its inability to transmit these high frequency components, the eye starts to close up as shown in Figure 4 (b). This phase delay is known as jitter in the time domain. This eye diagram, Figure 4 (b), is still acceptable (BER of 10⁻¹⁰ or better) for all but the most demanding applications.

As we turn to our investigation of the performance of sliding contacts in high speed data applications, we will discuss effects in both the frequency and time domain, but these are just two ways of looking at the same effects. When a slip ring is inserted into a transmission line, the primary issue is matching impedance of the line. Any device that represents an impedance mismatch will produce reflections at higher frequencies and result in phase delay (frequency domain) or jitter (time domain). So we will be exploring the impedance and variation of impedance with rotation of sliding contacts in this evaluation.



(a) Low jitter eye pattern



(b) Some jitter from phase delay

Figure 4. Eye Patterns

It is useful to consider the work that researchers in the area of stationary electrical contacts have done to understand the important characteristics of the contact zone on the ability of electrical contacts to transmit high speed data. This body of work serves as a good introduction to the critical parameters that need to be studied as we expand the discussion to sliding contacts. The discussion has expanded beyond DC electrical contact resistance (ECR) which has been the primary performance metric for electric contacts since Holm's famous book on electric contacts [11].

In his study of the failure of coaxial connectors, Sun [20] introduces the idea that in communication systems electrical contacts must be treated as an AC impedance and not just as a DC resistance. Early researchers who studied the capacitance of electrical contacts [21] [22] [23] and non-linear resistance effects [24] set the stage for consideration of the effect of these parameters on digital signals. By expanding a formula derived by Simmons [25], Takano [26] [27] showed that thin film layers in the contact zone distort the third harmonic of AC signals, and the thickness of these films can be measured by third harmonic distortion (THD) techniques. Since we've seen earlier that the third harmonic is a critical component of high speed data, distortion of the third harmonic could be a problem in high speed data transmission.

Lavers and Timsit [28] studied the relationship of signal frequency to the constriction resistance between two contacts and showed that value of constriction resistance is a function of signal frequency due to skin effects of high frequency signals. They reported the somewhat counterintuitive result that the constriction resistance decreases as the frequency increases in the actual contact zone, but when the constriction is considered in the bulk material around the contact the overall effect is an increase in contact resistance (they call this connection resistance) with frequency. A number of studies have investigated non-linear constriction resistance effects occurring at in the contact zone, and it is clear that any non-linear effects must be understood in digital systems to avoid unacceptable phase delays and jitter. Malucci [29] studied multipoint contact systems and discussed the relationship of frequency to resistance and capacitance of these multipoint contact systems.

A number of studies have expanded the understanding of contact impedance in static contacts to high speed digital data transmission [30] [31] [32] [33]. Also of interest is work that has studied the impact of contact impedance on RF connectors and MEMS devices [34] [35] [36]. What emerges from these studies on stationary high bandwidth electrical contacts is a picture of the contact zone shown in Figure 1 and the electrical model of Figure 10. The AC impedance between the two contacts is a function of frequency, contact geometry, surface roughness, surface films, and contact force. These factors are not much different than DC resistance considerations (with the exception of frequency) however the non-linearity of the constriction resistance and the reactance of the contacts add extra complexity to the studies. Based on this research on stationary contacts, it is clear that the primary area of concern in the study of high speed data through sliding contacts should be the change in the reactive elements of the contact impedance as well as the resistive that is introduced by the dynamic nature of the sliding contact.

As the sliding element of the electrical contact wipes across the stationary surface there are number of events occurring at the micro-level where the asperities meet that effect the impedance.

1. Surface films are being continually wiped off, re-formed, and/or re-deposited. The presence/absence, thickness, and chemistry of these films have an effect on both the capacitance and the tunneling resistance.

2. The surfaces are being altered by the wiping action; surface roughness is changing; adhesive debris (prows) are being formed, broken, and re-formed; and the contact area is changing.
3. Dynamic effects (stick slip, external vibration effects, surface run-out) are causing changes in the normal force pushing the contacts together.
4. Boundary lubrication parameters are being altered by surface physical and chemical changes, environmental conditions, and frictional and joule heating causing dramatic changes in the effect of lubricant [37, 38].
5. Wear debris and contaminating particles (conducting, semi-conducting and insulating) are finding their way between the contacts and being embedded into the boundary layer.

This paper will not focus on the causes of the changes in impedance but rather on the effect the impedance change has on the sliding electrical contact when inserted in a transmission line, but these tribological conditions underlie the discussion. This paper will investigate order of magnitude effects that could have an impact on data transmission to provide guidance for further in-depth study of potential issues. The advantage of digital data transmission compared to analog data is the relative immunity to signal noise events in the microvolt and millivolt range so we can turn our attention to events causing relatively large impedance changes (orders of magnitude). However, noise events in the nanosecond range can trigger bit errors, so we have to dramatically increase our measurement bandwidth over traditional studies to see them. Typical noise measurement bandwidths in studies as recent as 2012 [39] used a 30 kHz measurement bandwidth. Studies of data capability in the Ghz range require a measurement bandwidth of at least 6 orders of magnitude increase in this 30 kHz bandwidth.

III. SLIP RINGS AS TRANSMISSION LINES

When a slip ring is placed into a high speed data transmission line there are a number of macro design features related to high data interconnect practices [40] that need to be put in place to ensure proper operation. These practices are related to how the contacts are terminated and "wired into" the transmission line. These practices include impedance control, crosstalk protection, and proper shielding and grounding. However, the basic question of the ability of the sliding contacts themselves to handle high speed data is an issue that inevitably arises and is worthy of study. Is there some maximum data speed past which sliding electrical contacts can no longer be expected to operate reliably?

Passive circuit elements such as wires, circuit boards, and integrated circuit packages that interconnect active circuit elements in a digital system are called transmission lines, and most aspects of these transmission lines are well defined and characterized [40-45]. With the continued increase in data speed and system complexity, the properties of these transmission lines must be selected to minimize signal propagation degradation (e.g., ringing, reflections, and phase delay), interaction between signals (crosstalk), and electromagnetic interference from the environment. In some high performance systems these transmission lines require data

to be moved from a rotating platform to a stationary platform, and the most common method of de-rotating the data is through the use of a slip ring.

A slip ring is a complex electro-mechanical assembly that inevitably introduces some degree of reactance and non-linearity into the transmission lines. This is not a contact problem but rather an interconnect design problem. Good design practices can minimize these “lossy” and non-linear effects, but they cannot be eliminated.

Figure 5 illustrates a two terminal transmission line with a slip ring included. For simplicity, we assume that the transmission line itself is lossless [46] to investigate the slip ring’s effect on the characteristics of the transmission line. This is equivalent to the common practice of wiring a slip ring with a controlled impedance twisted pair cable (twinax).

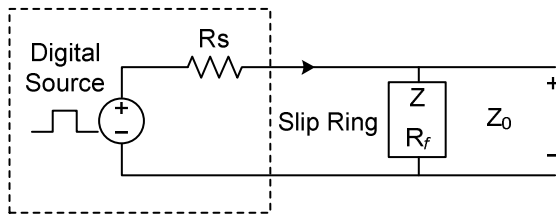


Figure 5. Two terminal block diagram

This paper will examine a specific slip ring design shown in Figure 6, a platter slip ring design. In a typical slip ring arrangement, each ring has two brushes per circuit contacting on the ring. In the case of our example, the brush itself is bifurcated, i.e., there are two distinct elements per brush. The bifurcation of each brush and the multiple brushes per ring provide redundancy and ameliorates the variations in contact parameters with rotation. Normally connection to the ring is accomplished in one location with a permanent connection, for example a wire soldered to a ring. As rotation occurs the change in the relative position between the brushes and the ring contact produces a variation in the electrical path length and a resistance variation [39]. Since rotational frequencies of slip rings are orders of magnitude slower than most data speeds and the amplitude of the variation is relatively small, this rotational variation in resistance can usually be ignored in high speed transmission line characterization.

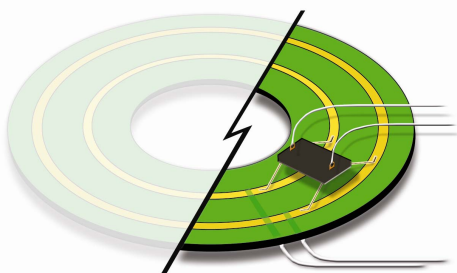


Figure 6. Illustration of a platter slip ring with a single ring pair. As the brush rotates around the ring the variation in length from the location of the ring lead termination to the brush lead termination in each direction can be a source of signal reflections.

However, this path length variation also produces two parallel paths from the brushes to the ring terminal that are of unequal and varying length, and this feature creates phase mismatching that can be significant on large diameters. Additional impedance mismatches can be created by wire and shield terminations and brush and ring impedance. A model of this slip ring configuration is illustrated in Figure 7, and traditional simulation tools can be utilized to simulate most of the circuit parameters [40, 47, 48]. Simulation of high speed interconnect circuits that contain “lossy” elements are discussed by researchers who are concerned with minimizing losses and signal distortion in electrical interconnects in the megahertz and gigahertz range and nanosecond and sub-nanosecond switching times. The lumped parameter method modeled in Figure 4 has been validated by a number of researchers [29-32]. But the circuit model needs parameters to “plug in” for sliding contacts themselves, and the digital designer turns to the electrical contact specialist for answers. How do sliding contacts behave when passing high speed digital data?

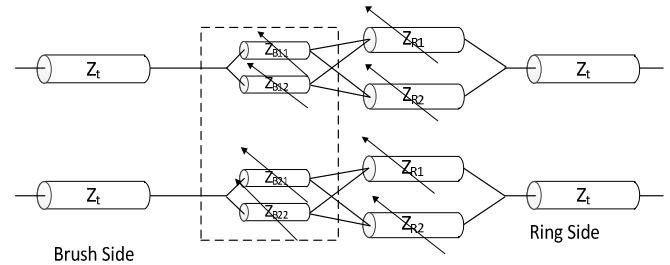


Figure 7. Electrical model of a slip ring assembly

An arrow through the impedance indicates a variable value.

A. Modeling Sliding Electrical Contacts

As outlined in the introduction, there is research on the modeling of stationary and switching contacts, but there is no published research on the high frequency modeling of sliding electrical contacts. Let us look at a typical contact surface that starts out with a surface roughness R_c of about $0.2 \mu\text{m}$. The most common ring surface is hard gold plate with a hardness of about $2 \times 10^9 \text{ N/m}^2$. The wiper (or brush) material again is normally a noble metal alloy, but soon after rotation starts a prow composed of ring material soon forms on the brush and the contact becomes prow-to-ring. The photomicrographs in Figure 8 show typical brush contact areas after several hundred hours of rotation at 30 RPM. These pictures illustrate very well the descriptions of Antler and others who describe ring material transferring to the brush to form a prow of laminar construction and subsequent sliding occurring between the brush prow and ring. This prow material is quite hard with measured hardness of roughly four times the hardness of the electro-deposited gold. The typical prow is about $6.5 \mu\text{m}$ thick and of various widths and lengths, although on average in the example slip ring these prows are about $200 \mu\text{m}$ in diameter.

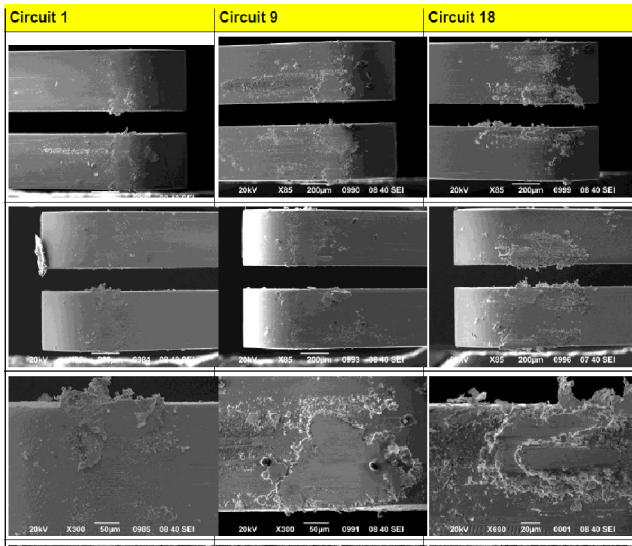


Figure 8. Brush contact areas

Figure 9 shows typical ring surfaces (there is no relationship between the brush and rings of these pictures). While the prow is forming on the brush, the ring is becoming “burnished”. The nodal finish formed by the electroplating (R_c of $0.2 \mu\text{m}$) is being worn smooth with rotation (compare Figure 9 (c) and (d)). In equilibrium conditions after prow formation, the system is a very hard and smooth prow sliding against a smooth ring surface. The prow can have hardness in excess of two times the hardness of the base material and the ring experiences work hardening at the contact surface. This system is typically lubricated with an ester-based lubricant that is applied only once in very low quantities. It is interesting to note the wide variability of the prow formation from brush to brush Figure 8. Although we can discuss “typical” prows, it is difficult to exactly characterize this prow. Some brushes build a distinct, well-defined prow and some seem to have a hard time getting a prow started.

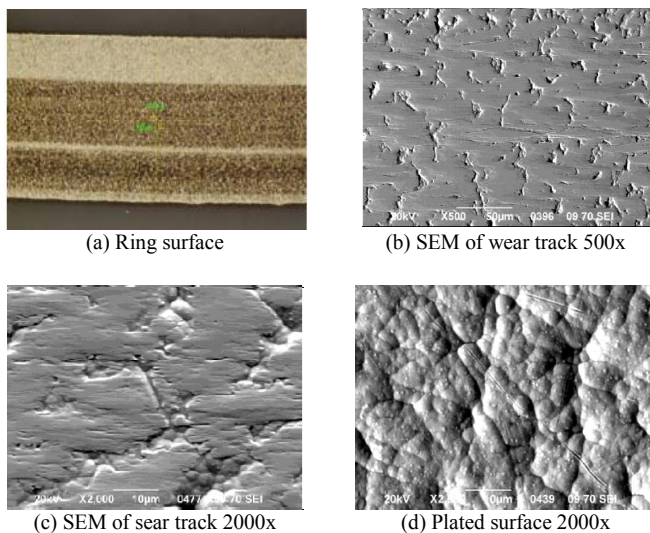


Figure 9. Ring surface

With this understanding of what the contact zone looks like, let us hypothesize that all three elements of circuit impedance (capacitance, inductance, and resistance) are present as shown in Figure 10 and then investigate this hypothesis. Resistance has been shown as two elements: DC resistance and non-linear resistance. Note that the inductance, non-linear resistance, and ohmic resistance are in series since these elements share the same current flow through the metallic contact. The capacitance is in parallel since this transmission path is coupling through the dielectric film and air in the non-contacting gaps as illustrated in Figure 1.

First we should investigate the decision to model the contacts on a macro scale rather than a micro scale. If all the action in the contact zone occurs on the asperity level or micro scale, how can we produce lumped parameters for the entire contact zone. Fortunately, there is evidence in the stationary contact research that this is a reasonable assumption. There have been a number of studies done using advanced numerical techniques such as finite element and finite difference analysis to show that results from micro models align with traditional macro models, certainly within the order of magnitude analysis we are performing [49-52]. With the goal of understanding the values for resistance, inductance, and capacitance (the elements of impedance) in the contact zone to use in the transmission line model of a slip ring, the lumped parameter approach will be taken.

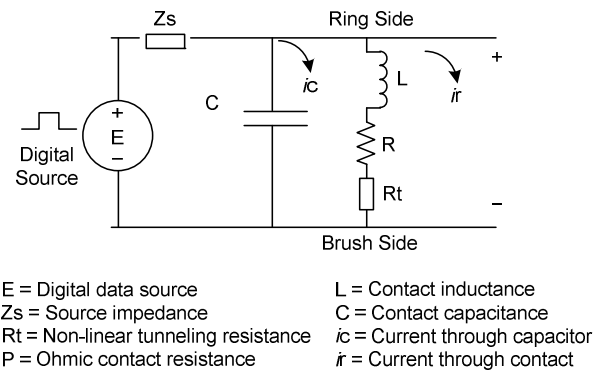


Figure 10. Electrical model of the contact zone

Malucci [30] studied the effect that contact parameters could have in the degradation of high data rate signals as modeled in Figure 10 although he, like most signal contact researchers, ignores the inductive component. The study bracketed the potential variation in impedance by assuming a purely resistive case, a purely capacitive case and one resistive/capacitive case, and the conclusion is that at high frequencies ohmic contact is not required to transmit data.

Chen reports similar results [31] and Smith [33] discusses the effect of nanosecond discontinuities in backplane connectors at Gigabit/sec data speeds. Gao [32] proposed an improved FEM model of stationary contact impedance and showed that degradation effects, when modeled as impedance changes, can have an effect on the reflected signal, the signal jitter, and ultimately the bit error rate (BER). Sun [20] also

models the effect of “contact failure”, i.e., high DC resistance, and shows the complex effect of the multi-reflections generated by these phenomena.

It is obvious that sliding contacts have a more active contact zone than stationary contacts, but the approach of bracketing the change in contact impedance between pure resistance and pure capacitance can be utilized. Since sliding has an effect on the rate of change of the impedance, it is also important to consider not just the amplitude of the impedance effects but the frequency components of nanosecond or microsecond events as well. Work has been done in the past by Mano [53] and Taniguchi [19] to describe the frequency components of sliding electrical contacts, and Maul [54] describes the intermittency phenomena of fretting contacts. It will be useful to combine these results from studies on ohmic noise with assumptions on capacitive coupling to understand more fully the frequency components of impedance.

1) Resistance

Electrical contact resistance is undoubtedly the most important element of sliding contact systems, and performance of sliding electrical contacts have typically been characterized by the variation in contact resistance (contact noise). This characterization has been in terms of linear (or ohmic) noise, but we will need to also look at non-linear resistance effects on the impedance.

Slip ring noise has always been considered a linear problem. Low noise, precision slip rings were developed in the analog world. Frequently these slip rings were inserted in front of any system gain, and any noise introduced in the system by the slip ring was amplified and was seen as sensor error. A typical specification on slip ring noise for these slip rings was 20 mΩ which would equate to μV of noise when passing mA signals. It is important to note that these systems typically had a very low frequency response, so that any noise above a few KHz was filtered out and had no effect. And since the noise was measured on analog oscilloscopes, noise in the MHz range was not recognized.

Digital data transmission through slip rings began to highlight the transmission line problems that slip rings can introduce. The problems can be grouped into two major areas. The first is the general transmission line problem caused by inserting an interconnect assembly with an unmatched and varying impedance into data transmission line of a characteristic impedance. This problem is addressed with appropriate high speed interconnect design practices. The second is the contact noise problem. The critical digital sliding contact noise parameters are significantly different than with analog data. The discussion shifts from an amplitude problem to a frequency problem. Contact noise in the 20 mΩ range is well under the noise floor of digital signals, but noise in the MHz range can produce bit errors with data in the Mbit/sec range.

What are reasonable lumped ohmic resistance values produced by healthy sliding contacts and how do these values change over time? As a matter of fact the term contact noise has less value in the digital discussion as the term intermittence. We are again borrowing from the stationary

contact research, and the term intermittence has been used to define failure in connectors especially connectors experiencing fretting wear. ‘Intermittence’ can be defined as a short-duration occurrence of high resistance in an electrical contact. It is important to understand that the terms “high resistance” and “short duration” are both dependent upon the signal level and signal speed. For example, intermittence values on the order of the signal rise time and 10dB down from the signal level could significantly increase the jitter level of the signal and increase the BER.

In our example platter slip ring we can estimate the stationary contact resistance using fairly traditional methods. The estimated contact area can be found using Tabor’s classic formula $A = F/H$ where A is the estimated real area of contact, F is the brush force, and H is the hardness of the ring material. For this case, the estimated area is roughly 2.5×10^{-12} m. If we assume that the contact area is circular and the contact is equally distributed across this area, then we can use Holms [11] simple formula to estimate the contact resistance $R = \rho/2a$ where R is the contact resistance, ρ is the electrical resistivity, and a is the spot radius. For our example the estimated resistance is 4 mΩ per contact or 2 mΩ for the bifurcated brush. This very basic analysis is fine for our use since our primary concern is the variation with rotation.

Figure 11 shows the calculated effect of brush force variation on contact resistance and contact spot size. A main cause for intermittences during rotation is the variation of contact force caused by vibration of the brush from stick slip or environmental conditions. If we use our 10 dB threshold value for intermittences and assume a signal voltage and current level of 5 volts and 10 mA, the brush force variation has to be around 9 orders of magnitude to get the ~50 Ω resistance that would yield a .5 volt drop across the contact. The approximate contact spot size at this contact resistance is on the order of magnitude of 0.0001 μ.

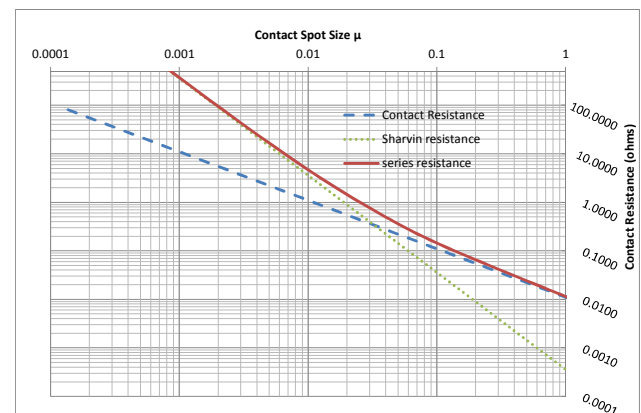


Figure 11. Contact resistance and contact radius as a function of brush force

This traditional analysis of contact resistance assumes that the spot size of the contact is significantly larger than the mean free path of electrons. When the contact size is reduced to a distance smaller than the mean free path of electrons, the

Sharvin effect can be the primary component of resistance [12]. This effect results in a transition of the conduction properties in the region near the contact spot from a continuum (a) to a ballistic (b) regime.

Timsit discusses this effect [55] and simplifies the Sharvin equation to

$$R_s = C / a^2 \quad (1)$$

where C is a constant dependent only upon the electronic properties of the material and a is the contact spot size. In the case of gold the value of this constant is 3.58×10^{-16} ohm meter². Figure 12 shows this Sharvin resistance component of resistance and the significance can be seen when the contact spot is sub-micron. The standard ohmic resistance and Sharvin resistance can be evaluated as a series resistance as shown in Figure 13 and the sum of these two resistance values are shown in Figure 11.

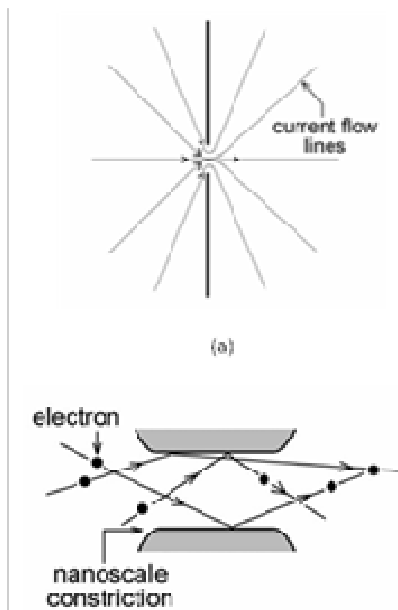


Figure 12. Illustration of Sharvin resistance: (a) shows the current flow in standard ohmic contact; and (b) shows configuration of non-ohmic contact

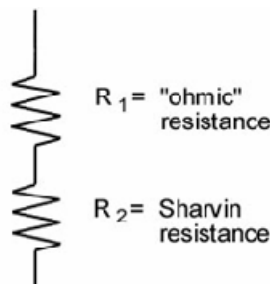


Figure 13. Contact resistance [55]

Timsit argues that Sharvin resistance is the likely explanation of the apparent breakdown in the classical contact

theory in the reporting of contact intermittences by Maul, et al [54, 56, 57] and this analysis shows that Sharvin resistance levels leading to the 10dB intermittence level results in a spot size of at least two orders of magnitude less than the Holm constriction resistance spot size. Since our assumption that all the contact is centralized in one large spot, it is likely that the Sharvin resistance is actually a bigger component of the resistance in actual multi-spot contacts.

2) Non-linear resistance

There are a number of effects in play in this constriction region which result in a non-linear component of the resistance.

a) AC signal frequency leads to skin effects in the constriction region [58] and produce a frequency dependent component of constriction resistance. There are actually two parts to this constriction resistance: the resistance at the constriction itself and the tunnel area as the current expands into the bulk material through the constriction. Under DC and low frequency conditions the current flow near the contact spot spreads widely into the volume on both sides of the constriction. However at high frequencies, the skin effects limit the ability of the current to expand into the bulk material thereby increasing the effective resistance. There is some evidence to suggest that the resistance at the actual constriction decreases at increased frequencies [13] but this increase in the bulk resistance component results in an increase in constriction resistance as frequencies increase.

b) Joule heating. The resistance non-linearity generated in the contact zone by a sinusoidal signal has been shown to be a function of the signal frequency as well as the higher order harmonics [59-61] due to the sine variation in the joule heating at the contacts zone [13]. Of course in the case of square waves this relationship becomes more complicated by the multiple sine components of the square wave.

As is the case with many non-linear phenomena there are no good analytical methods to estimate these non-linear effects and empirical data relevant to our sliding contact arena is very limited. It is clear that the primary effect of impedance variation with frequency on our high data rate contacts will be on signal phasing, i.e., jitter.

Our initial assumption driving the variation in contact resistance was a change in brush force with rotation. There are a number of other causes for the increase in contact resistance that have been studied, and for our purposes it is sufficient to understand that increased resistance results from a smaller metal-to-metal contact area for whatever reason and this metal to metal contact can be replaced by film conduction, high resistance particle contact or simply by air.

3) Capacitance

The studies on contact capacitance are normally divided into three groups: Metal-Insulator-Metal (MIM), Metal-Oxide-Metal (MOM), and Metal-Gas or liquid insulating material surrounding the contact-Metal (MGM). All three of these relate to a typical slip ring application.

- **MIM:** Slip ring designers have dealt with insulating films since the early days of slip ring research. Frictional

polymers (Abbott), co-deposited plated organics [62], and chemisorbed and physisorbed organics and water vapors all contribute to the insulating film.

- *MOM*: Oxide films form on even the most noble of contact materials. These are oxides of the primary contact materials as well as oxides of alloying metals and contaminants.
- *MGM*: Slip rings are usually lubricated with a liquid lubricant [63, 64] although this lubrication would best be described as a boundary lubrication scheme [37].

The capacitance, C , between two flat parallel surfaces that overlap with some gap between them is given by

$$C = \epsilon_r \epsilon_a * A / h \quad (2)$$

where $\epsilon_r \epsilon_a$ is the product of the relative electrical permittivity of the material in the gap and the permittivity of air, A is the overlap area, and h is the distance between the two surfaces. As we have pointed out the landscape between the contacting surfaces is complex from a geometry and chemistry standpoint so we have to make some simplifying assumptions to proceed. Researchers have studied the contact region to determine the effect of films and contact geometry [21-23, 65-70]. Recently work has been done to generalize the classic work by Holm on the a-spot to include a finite axial length [49] which produces the model shown in Figure 14 which results in an equation for the capacitance of $C_c = C_b + C_v$

$$C_b = \epsilon \frac{\pi a^2}{2h}, \quad C_v = \epsilon_a \frac{\pi(b^2 - a^2)}{2h} \quad (3)$$

where C_b is the capacitance of the bridge, and C_v is the capacitance of the noncontact region shown in Figure 14 and ϵ is the permittivity of the connecting bridge.

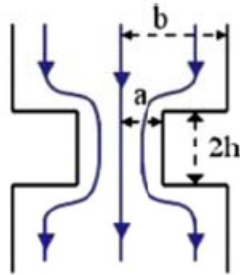


Figure 14. Model of contact zone with a-spots of finite length

Our goal is to determine the order of magnitude effect that capacitance could have on our contacts at high data rates, so we will take a more approximate approach and use equation 2. From a visual inspection of the wear scar on the brush and the wear track on the ring, we can estimate the approximate brush area that is in proximity to the ring which appears to be a rectangular area of about $200\mu \times 762\mu$ or $1.52 \times 10^{-7} \text{ m}^2$ (see Figure 15). We have already determined that the area of contact is less than 1% of this “apparent” area of contact, so we can safely assume that all the area is available for capacitive

coupling, we’ll make four additional assumptions to bracket the possible capacitance of this contact region:

1. The prow is fully established. In this case the measure height of the prow is about 6.7μ which in effect establishes the h dimension. We assume the permittivity of air.
2. The prow is fully established and a lubricant film exists in the gap. We assume a relative permittivity of 5 for typical ester lubricants.
3. The prow is not established and the average surface roughness is the dimension that establishes the effective gap of between the contacts. We assume the permittivity of air.
4. The prow is not established and a lubricant film fills the gaps between the contacting spots.

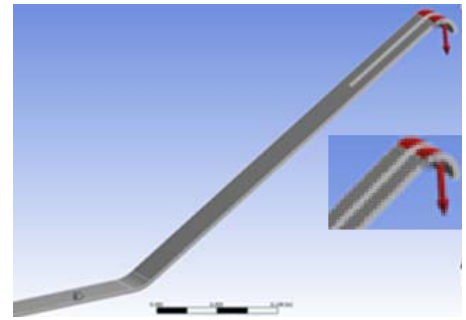


Figure 15. Region of apparent contact area (estimated area for capacitive coupling)

TABLE 1: ESTIMATED CAPACITANCE OF CONTACT ZONE

Assumption	Capacitance (pf)
Full prow, air	0.2
Full prow, lube	1.0
No prow, air	13.3
No prow, lube	66.4

Table 1 shows the calculated value for each of the assumptions listed. It is clear that the chemistry of the zone is more complicated than the assumption of either air or lubricant, but these two options provide sufficient order of magnitude bracketing of potential capacitance variation. If we look at the capacitive reactance resulting from these capacitance values at frequencies from 10 to 1000 MHz we get the results shown in Figure 16. We use the standard formula for capacitive reactance (Z_C) of:

$$Z_C = (2\pi f C)^{-1} \quad (4)$$

where f is the frequency in Hz and C is the capacitance in farads. It is useful to compare these capacitive reactance values to the resistance value (50Ω) that we earlier defined as the intermittence threshold. At lower frequencies the capacitive reactance is sufficiently high that that gap/dielectric looks like

an open circuit. However, at higher frequencies and under the assumptions of higher capacitance (smaller gap between the brush and ring) when the capacitive reactance value approaches that of the parallel resistance, the signal can be transmitted through the dielectric in the gap.

4) Inductance

The primary interest in contact inductance in electrical contacts is in power transfer. Large changes in inductive reactance in the contact region with high current levels can result in damaging current surges. In the case of low level digital signals, this potential does not exist. One method of evaluating the order of magnitude of the potential of inductive noise resulting from variation in induction due to sliding is to use [49]

$$L_c = h \left(\frac{\mu_0}{\pi} \right) \ln \left(\frac{b}{a} \right) \quad (5)$$

where h is the $\frac{1}{2}$ of the height of the contact point, μ_0 is the magnetic permeability of gold (1.26×10^{-6} H/m), and b and a are the radii shown in Figure 14. For the purpose of this calculation we have estimated the ratio of the two radii as 10. This value can be adjusted to account for skin effects using a method found in [13] to adjust both a and b radii for skin effects. The variation in the resultant reactive inductance for our frequency range is found in Figure 16.

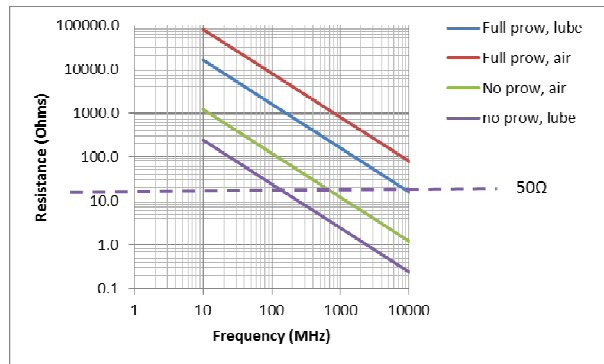


Figure 16. Capacitive reactance for assumptions of Table 1

TABLE 2: INDUCTIVE REACTANCE AS A FUNCTION OF FREQUENCY

Frequency	Inductive reactance (mΩ)
10	0.3
100	1.0
1000	3.2
10000	10.1

Since this inductance is in series with the resistance terms the low value of reactive inductance across the frequency range suggests that inductance will have negligible effect on contact intermittence when we are using a threshold of ~ 50 ohms as the threshold impedance value. Inductance will play a role in overall slip ring system analysis, but in terms of the contact itself we will ignore the effect of inductance.

IV. EXPERIMENTAL

An experiment was conducted to help understand if the parameters that had the potential for affecting slip ring performance at high data rates actually do play a role. The test set up is shown in Figure 17. The signal generator energizes the ring with respect to ground with a 1-Vpp signal, sine or square wave. The two brushes are connected to ground through 100-Ohm resistors, which gives the return path to the generator and allows a noise-cancelling differential connection to the instrumentation amplifier. Connected as shown, the fundamental signal is largely cancelled, but individual variations in brush signals do not cancel and can be detected without the large fundamental. Disconnecting either the + or - connection unbalances the circuit and allows a single contact to be tested. The signal generator can generate both sine wave and square waves, with adjustable amplitude and frequency. The signal generator normally sees a proper 50-Ohm termination because of the two resistors in parallel.

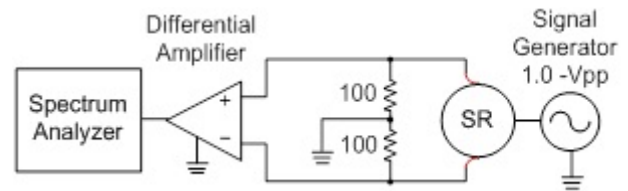


Figure 17. Contact test setup

Tests were performed with a 500 KHz signal at 3 different brush force values. The goal was to determine what effect degraded contacts had on the signal quality; the method used to simulate “degraded” contacts was to reduce the nominal brush force. Tests were run at an established design force (F_d), $0.6 F_d$, and $0.2 F_d$. To provide additional “degrading” affect only one of the halves of the bifurcated brush is in contact with the ring.

The results from the $0.2 F_d$ tests are the most instructive. Figure 18 shows the results of a DC noise test with very low resistive noise variation with rotation even at 20% of normal brush force. One set of data is stationary (test 1) and other two sets are rotating. There is no appreciable difference between the two data sets. This is not surprising since sliding contacts can tolerate a wide variation in brush force when uncontaminated and when properly lubricated. However, Figure 19 shows noise results from a test using a 0.5 Mhz sine wave as the primary signal with the same light brush force. The blue dotted line shows frequency components of the noise with the contacts stationary; this is the reference curve. The red solid line shows data from the rotating contact test. The secondary axis shows the values of the difference function. Some frequency spreading due to intermodulation effects of the resistive noise can be seen around the 0.5 Mhz signal frequency and the signal amplitude is decremented by about 15 dB. The total effect is a decrease in signal to noise ratio from about 45 dB to 20 dB. Data showing frequency spreading at the 1st and 3rd fundamental of a 500 Mhz square wave can be seen in Figure 20. This represents a rise in the noise floor of about 20 dB.

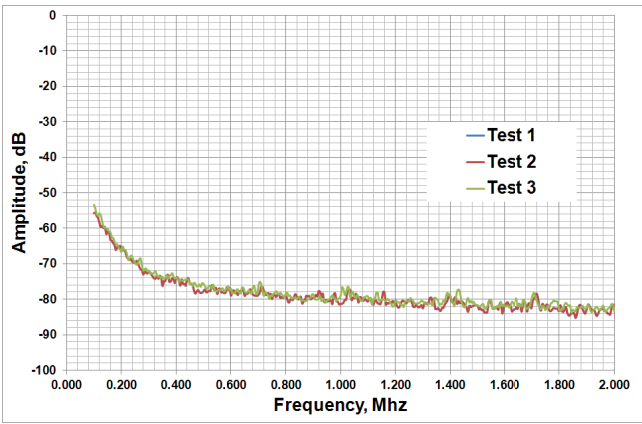


Figure 18. DC noise test with 0.2 F_d brush force

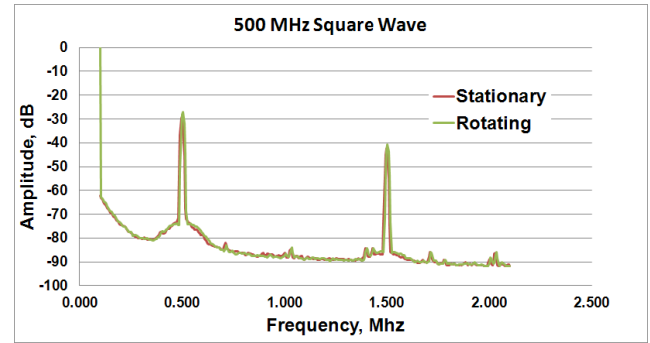


Figure 21. Square wave data with 0.6 F_d brush force

V. CONCLUSION

We have provided an order of magnitude analysis of the properties of the zone of contact of a sliding electrical contact system that could affect the impedance of the contacts and subsequently the ability of the sliding contacts to transmit high speed data. The following conclusions were reached.

A slip ring is a complex interconnect problem in a high speed data transmission line, and the sliding contact model is only one of the impedance issues that must be addressed for proper operation.

The variation in AC impedance is the key parameter to be examined when evaluating sliding electrical contacts for suitability to carry digital data.

While capacitance can have a significant effect in stationary contacts with relatively large capacitive coupling area, this coupling area is minimal in sliding contacts and capacitance will likely play a minimal role unless the frequency is well over 1 Ghz. In the case of contact degradation, the increased dielectric value between the contacts could lead to higher capacitive reactance and shunting of higher frequency components.

Inductance in the contact zone is very low and in series with the resistance and should play no appreciable role in the variation in contact impedance with rotation.

The analyses reviewed in this paper indicate that resistive effects continue to be the major parameter that should be used to characterize sliding contact performance. However, Sharvin resistance and non-linear frequency dependent resistance, in addition to ohmic resistance, can be factors when sliding electrical contacts are transmitting digital data.

Intermittences are the primary issue with digital data transmission through electrical contacts. An obvious source of these intermittences is insufficient metal to metal contact leading to voltage drops in excess of the threshold value.

Experimental data shows that when the contact force is reduced frequency intermodulation effects cause noise near the fundamental frequencies of a square wave leading to a rise in the noise floor.

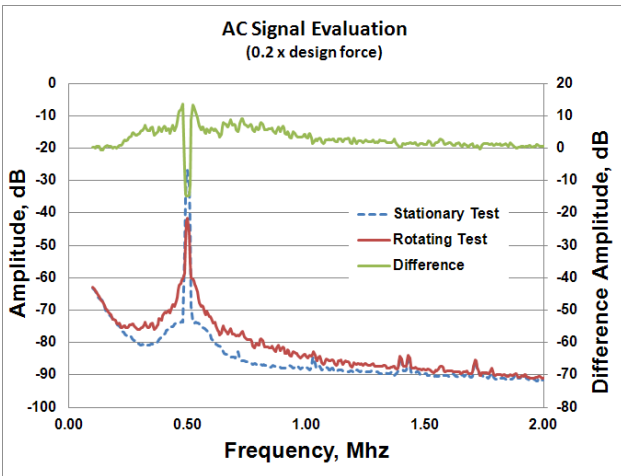


Figure 19. Sine wave noise test

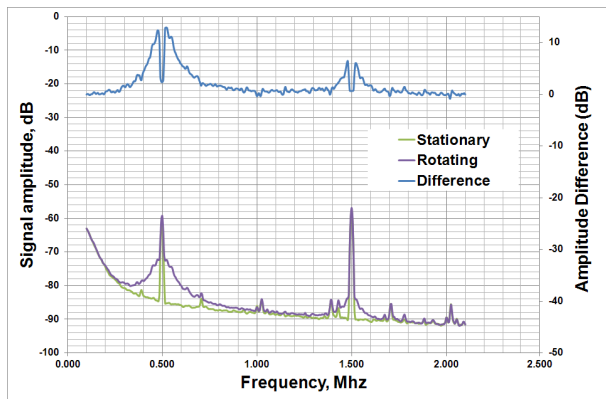


Figure 20. Square wave noise test at 0.2 F_d brush force

The data from the 0.2 F_d test can be compared to data from the 0.6 F_d as found in Figure 21. These two data sets (one stationary and one rotating) show no appreciable difference in the two curves. There is no frequency spreading as was seen in Figure 21.

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