Asociación Argentina de Mecánica Computacional

Mecánica Computacional Vol XXVI, pp.2728-2741
Sergio A. Elaskar, Elvio A. Pilotta, Germán A. Torres (Eds.)
Córdoba, Argentina, Octubre 2007

ANALYSIS OF LARGE SETS OF SEEMINGLY-RANDOM EXPERIMENTAL DATA: THE CASE OF ELECTRON EMISSION FROM FRICTIONAL CONTACTS

Gustavo J. Molina

Department of Mechanical and Electrical Engineering Technology, Georgia Southern University, Statesboro, Georgia 30460-8045, USA, gmolina@georgiasouthern.edu

Keywords: triboemission, deterministic-chaos, Shannon's Spectral Entropy.

Abstract. Analysis of seemingly random experimental data can be difficult when no phenomenological model is known. If available data is output for even simple but unknown-dynamics systems, hypotheses could be made and tested for possible underlying processes, being them from pure random to deterministic ones, but testing of such hypotheses can be difficult in the practice. For instance, the study of theoretical systems leading to chaos is an established mathematical field, but the testing of given experimental data for the hypotheses of deterministic origin versus a stochastic one is not simple and it may not be possible. Available analysis techniques are reviewed and discussed.

The author and colleagues have carried out extensive experimental research work on emission of electrons as a probe for in-situ on-time surface monitoring, seeking a better understanding of this triboemission from dry-sliding contacts and during wear, and of the fractoemission that occurs during plastic deformation and failure. Particle outputs may be very complex and carry limited information; Electron triboemission data are typically composed of seemingly deterministic bursts of emission which are superimposed to lower but seemingly constant levels of random emission. They are large sets that are acquired in very short-time windows, were the discrete occurrence of counts is matched to detected particles, but no information about their energy or paths can be simultaneously obtained.

Analysis of triboemission outputs required new approaches and techniques: the author studied different stochastic-process distributions for fitting to such data, and he also tested the hypothesis of deterministic-chaos origin. The proposed data analysis can be tools for the study of similar complex systems. For instance, the author believes that understanding of triboemission and of related mechanisms is a key to modeling of frictional and charging processes for insulators, mainly for ceramics, and for semiconductors.

1 INTRODUCTION

Experimental investigation of physical-system evolution is carried out by finite-window sampling which leads to sequences of real numbers. These sequences are recorded as time series, and they are analyzed to obtain insight about the system dynamics. But for even simple systems the actual experimental outputs can be far from the clean (e.g., non-noisy) sequences one would expect. If no phenomenological model of the system is known, the investigator could still hypothesize the system evolution to be either deterministic or mainly random, and it can be expected that the experimental outputs would reflect such nature. But actual outputs almost always contain a superimposed component of noise of unknown origin; this component can be deterministic, random, or a combination of both.

If signal noise be filtered out, experimental outputs would show neither as clean periodical signals (e.g., of deterministic origin) nor as fully random sequences, because rather simple deterministic-systems can be strongly sensitive on initial conditions. One reason for such sensitivity is non-linearity of underlying dynamics processes. The outputs from these so-called “deterministic chaos” systems seem random but they are the result of deterministic interactions, and the corresponding system dynamics is called deterministic chaos dynamics. For experimental systems presenting deterministic chaos, the evolution and final state cannot be predicted. No matter how similar two sets of initial conditions are, the time sequences will become different over a period of time. This paper briefly reviews and discusses some available techniques for investigating hypotheses about experimentally obtained time series. It also deals with the phenomenon of electron emission from frictional contacts as a presented analysis case.

1.1 Triboemission research

Triboemission is defined as the emission of electrons, ions, neutral particles, photons, radiation and acoustic emission under conditions of tribological damage, in particular when an insulator or semiconductor material surface is disturbed. Figure 1 shows a conceptual view of triboemission.

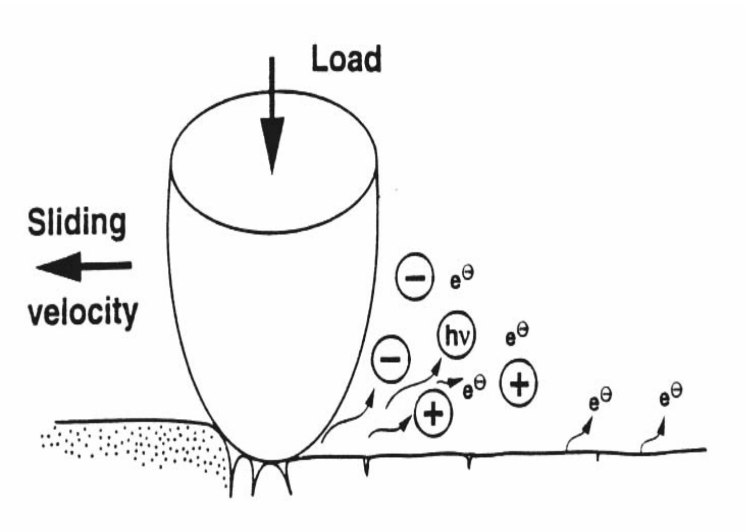

Figure 1. Conceptual view of triboemission

Triboemitted electrons, which make the majority of charge-triboparticle emission from insulators and semiconductors, are known to be important factors in, for instance, the initiation and control of tribochemical reactions during lubrication processes (Furey et al., 1997; Kajdas et al., 2002). They are a promising probe for in-situ on-time monitoring of surface-change dynamics. Research work on charged-particle triboemission were carried out by Nakayama et al. (1997) and Nakayama and Fujimoto (2004), by Kim, Langford and Dickinson (1995), and by Molina et al. (2001). The latter developed a high vacuum tribometer for triboemission studies and carried out extensive measurements of electron triboemission from the scratching of ceramics and semiconductor, the obtained outputs being burst-type time series.

Triboemission particle outputs carry limited information while their time evolution is very complex; they are typically composed of seemingly deterministic bursts of electron triboemission which are superimposed to lower but seemingly constant levels of seemingly random emission. In the experimental work of the author outputs are large sets which are acquired in very short-time windows, in which the discrete occurrence of particles is matched to counts, but no information about their energy or paths can be simultaneously obtained. Stochastic analysis of the corresponding frequency-domain distribution for typical triboemission count-pulse outputs suggested that their occurrence is not fully random. Therefore, the hypothesis also was studied of deterministic-chaos origin for triboemission data.

The work of Molina et al. characterized burst-type negatively-charged triboemission under high vacuum for diamond-scratching at constant load and speed of the insulators alumina, sapphire (Molina et al., 2001) and silicon nitride (Molina et al., 2004a) and the semiconductors Si and Ge (Molina et al., 2004b), and for an alumina-ball sliding on an alumina-disk (Molina et al., 2005). They found that for the tested contact conditions positively-charged emission from insulators were negligible and metals were not known to produce significant triboemission (Molina et al., 2001). They also measured, by retarded-energy technique, large fractions of low-energy triboelectrons (e.g., 1 to 5eV) for alumina and sapphire scratching and their spectra extending beyond the largest set potential (e.g., 48eV); Nakayama and Fujimoto's (2004) tribolectron-energy measurements were found consistent. Although electron-triboemission origin is still unclear, it is apparent that an important fraction of the electron output is emitted for energies lower than the electron work function (WF) of the bulk insulator materials. Early "conceptual mechanisms" for triboemission (Nakayama et al., 1997; Dickinson et al., 1983) do not explain the lower electron work-function values.

Dickinson et al. (1983) extensively studied the connected phenomenon of fractoemission from the tensile or bending fracture of oxides, polymers and their composites. They hypothesized that microfracture and dielectric breakdown may be the origin of fractoemission, but they also suggested that strained surface should grow surface defects that would locally reduce the surface work-function (WF). More recently Molina et al. (2007) proposed a triboemission mechanism where reduction of WF (due to plastic deformation and increased dislocation density during sliding), and the surface charging are essential to electron triboemission from insulators. They experimentally showed that the first occurrence of large bursts of electron triboemission correlates with the onset of wear (Molina et al., 2005). This mechanism is consistent with triboemission data during contact and after-contact for insulators and semiconductors and with the triboelectron-energy measurements.

1.2 Analysis of experimentally obtained time series

In the case of phenomena whose underlying processes are known or assumed mostly random, the investigator usually makes hypotheses on the underlying random components, to then test the fitting of appropriate distributions. Such distributions are derived from assumptions about the corresponding physical processes and from the observation of data; frequency descriptions of the output often guide the choice of candidate distributions. A main problem to such approach is that experimental outputs may contain superimposed deterministic noise. The experimental section of this paper discusses stochastic analysis of the triboemission outputs by fitting to selected distributions.

A dynamical system evolves as a set of possible states according to a rule that determines the present state in term of past states. The study of theoretical systems leading to deterministic chaos is an established mathematical field; i.e., see Alligood, Sauer, and Yorke (1996). But the testing of experimental data for the hypotheses of deterministic origin versus a stochastic one is not simple and often not possible. Pincus (1991) analyzed the problems of testing experimental time-series data and showed that even for low-dimensional systems, the number of values needed to correctly apply the algorithms grow exponentially with the number of dimensions.

An additional problem with experimental data is that the number of dimensions is likely unknown and their estimation is difficult. Available dimension algorithms are, for instance, correlation dimension and Lyapunov spectra; i.e., see Abarbanel (1996). Pincus and Huang (1992) demonstrated that chaos cannot be proved from experimental data. They proposed solving the problem of studying the deterministic-origin of experimental data by distinguishing among different complex-system data (e.g., from periodic to fully random) by parameter estimation.

The seldom-solvable problem of "testing chaos" has recently led to the more general one of quantifying the irregularity of assumed stochastic signals. One classic concept for such quantification is entropy. Entropy, when considered as a physical concept, is proportional to the logarithm of the number of microstates available to a thermodynamic system, and is often interpreted as a measure of the amount of "disorder" in a system. Entropy is an intuitive measure in the sense that one could visually distinguish a regular signal from an irregular one. It also has the relevant property of being independent of absolute scales such as the amplitude or the frequency of the signal. In the practice entropy values may be dependent on the sampling-window, but such property may allow an estimation of "periodicity" in experimental data.

Kolmogorov and Sinai early proposed the K-S entropy algorithm to classify deterministic systems. However, the K-S entropy was not designed for statistical estimation (e.g., see Abarbanel, 1996; Pincus and Huang, 1992). Eckmann and Ruelle introduced the E-R entropy algorithm on the assumption that a physical invariant (i.e., a deterministic component) underlies in the distribution of experimental data. But E-R entropy is always infinite for a process with superimposed random noise (e.g., see Pincus and Huang, 1992).

The Approximate Entropy (ApE) algorithm developed by Pincus (1991), which yields finite values for both deterministic and random data, gives increasing ApE values to intuitively increasing data complexity. However, these formulations do not consider the relationships that scaling has with disorder and entropy. And although Pincus' ApE has been proved a robust parameter for process classification, the unknown remains of how ApE can be affected by "truly" random noise. The study of ApE performance may be done at best for its quantification of simulated chaotic data, which cannot include actual random noise but a "simulated noise" that is deterministic from the mathematical basis of the random-number generator.

Entropy metrics are of growing importance to information theory. Shannon and Weaver (1949) defined a measure of entropy from the concept of information as a statistical phenomenon. The most general definition of Shannon's Entropy (H), which matches some of the thermodynamics ones, represents a quantitative measure of uncertainty associated with the frequencies of occurrence p of all considered categories:

$$H = \sum_i \{ (p_i) \log (p_i) \} \tag{1}$$

where the summation is over all the categories and p_i is the relative frequency of the ith category.

When applied to an information source, such entropy is a measure of the information contained in a message (or signal), which is different than the portion of the message that is strictly determined by inherent structures (i.e., the periodical portion of a signal, that is predictable). Information-theory entropy was first applied to a signal power-spectrum by Johnson and Shore (1984). In frequency domain, the Shannon's Spectral Entropy (SSE) is a measure of the irregularity, complexity, or unpredictability characteristics of a signal. In general, the starting point of the SSE computation is the spectrum of the signal. For triboemission outputs, such power spectrum is a discrete distribution obtained for the frequencies of observed windows with a given count (Molina et al., 2003). A normalized power spectrum is computed by setting a normalization procedure so that the sum of the normalized power spectrum over the selected frequency region [f_1 , f_2] is equal to one. For triboemission outputs such normalization is carried out by simply dividing each frequency by the total number of counts; the considered frequencies range between the zero-count frequency (which is relevant for short sampling windows) and the largest observed one. Normalized values are experimental estimations of the probabilities of occurrence for a number of counts (e.g., of detected electrons) in the window (Molina et al., 2003).

The spectral entropy SE[f_1 , f_2] corresponding to the frequency range [f_1 , f_2] is computed as a sum:

$$SE[f1, f2] = \sum_i \{ P(f_i) \log (\frac{1}{P(f_i)}) \} \tag{2}$$

where $P(f_1)$ is the normalized power spectra for frequency f_1. Between all considered frequencies [f_1 , f_2] the Shannon spectral entropy SSE(N) for the spectrum is computed as:

$$SSE[N] = \frac{SE[f1, f2]}{\log(N\,|f1, f2|)} \tag{3}$$

where N | f_1 , f_2| is the total number of non-zero frequency components in the range [f_1 , f_2].

A signal in which sequence values are truly random has maximum complexity and maximum SSE of one (as in the case of white noise spectrum), while for a fully periodical signal the SSE is zero. The SSE of, for instance, a Poisson distribution increases for larger mean rate (e.g., it depends on the sampling window for experimental data), but a practical limit of the SSE for a Poisson's is of about 0.6.

2 EXPERIMENTAL

2.1 Experimental setup and conditions and typical triboemission data

The triboemission instrument developed by Molina et al. (2001) was used for negative-charge intensity measurements from diamond-cone or alumina-ball scratching of ceramic and semiconductor rotating disks in a vacuum of 10^{-6} Pascal or better. A channel electron multiplier (CEM) detector in the pulse-counting mode was operated at 2750V and a +200V input bias. Individual charged-particles reaching the CEM are detected as individual counts in windows as short as 10 milliseconds. Instrument features are presented by Molina (2000).

The contact geometries consisted of rotating 25.4mm-diameter-disks of amorphous alumina, sapphire, Si_3N_4 , and Si and Ge, that were scratched by fixed pins: either a conical diamond stylus of 90-degree angle and nominal 0.060-inch tip (supplied by Bruce Diamonds) or a 0.125-inch diameter alumina-ball (99.5% alumina, grade 25, supplied by LSP Industrial Ceramics Inc.). The alumina disks used in this study, consisting of 99.5% isostatically-pressed polycrystalline alumina with a ground surface to an average CLA roughness of 0.50–0.65 micrometers, were supplied from LSP Industrial Ceramics Inc. The sapphire disks were optically flat, of anisotropic unicrystalline aluminum oxide and obtained from the General Ruby and Sapphire Corporation. The semiconductors Si and Ge (of disk thickness of 2mm and 3mm respectively) were supplied by Infrared Optical Products as plane mirror-polished windows of IR-reflecting quality (n-type optical grade Si and Ge of resistivity 5 to 40 Ohm-cm). Silicon nitride disks (99.9% purity of dielectric constant 7.9) were supplied by International Ceramic Engineering.

Constant rotational speeds (2 to 10rpm for linear speeds of 0.096 to 0.48 cm/s at the circular wear track) and loads (2 to 5N for diamond-cone and 10N alumina-ball sliding) were applied. For each measurement, an initial background-reference was taken for 10 to 30 seconds; background-noise was less than 0.1count/sec. The contact was then applied for varied sliding periods; typical electron triboemission outputs are shown in figures 2 to 4.

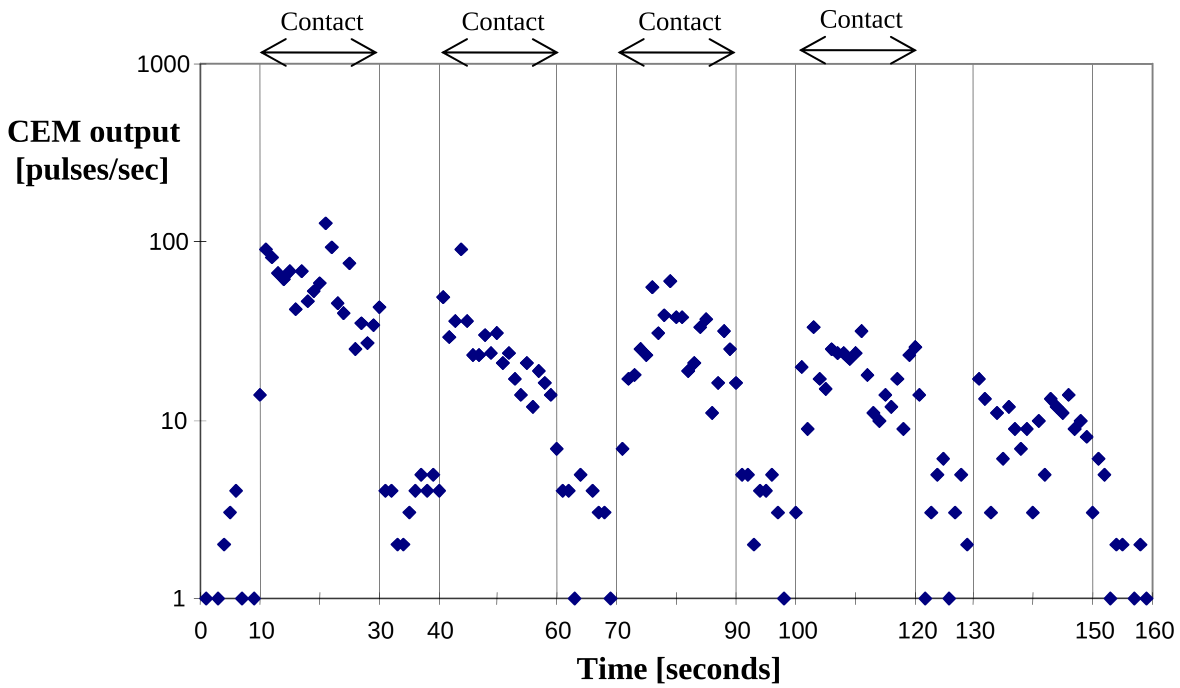

Figure 2. Negatively-charged triboemission (CEM-count for no grounded grid) for diamond-on-alumina sliding contact. 20second-periods of sliding contact are followed by 10-second periods of no-contact. Load: 2N . Speed: 0.14 cm/s. Acquisition window: 10mseconds

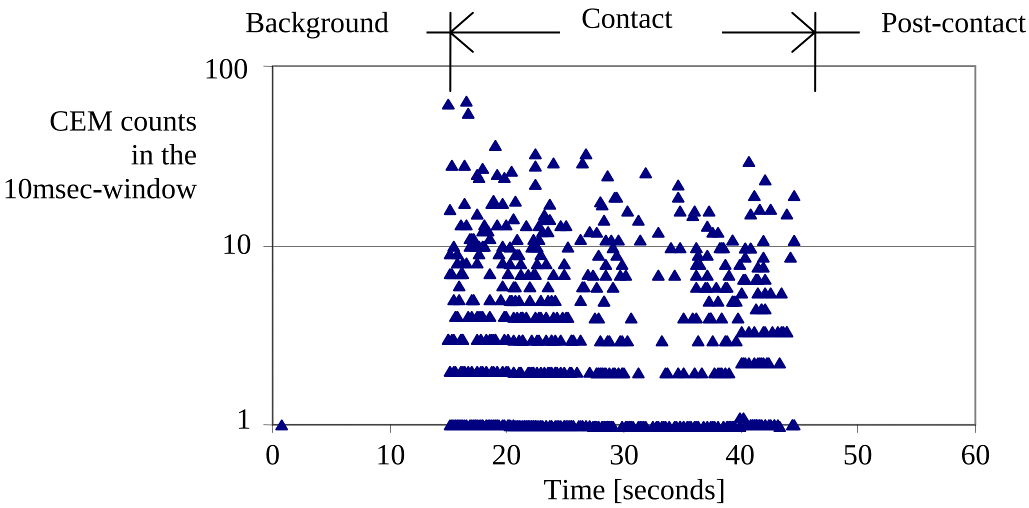

Figure 3. Negatively-charged triboemission from diamond-on-Si sliding contact.
Acquisition window: 10msec. Load: 5N. Speed: 1.0mm/s.

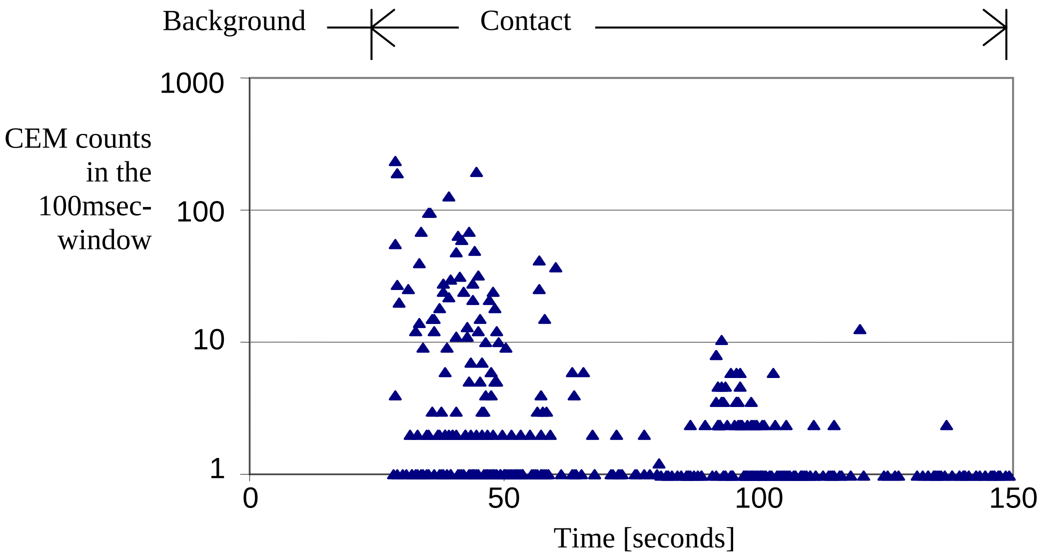

Figure 4. Negatively-charged triboemission (CEM-count) for diamond-on- Si_3N_4.
Acquisition window: 100msec. Load: 5N. Speed: 1.0mm/s.

Figures 2 to 4 show that the measured negatively-charged triboemission outputs are clearly associated with sliding contact. Triboemission rates and statistical significance of these experiments are presented by Molina (2000). Some outputs also may include sporadic superimposed large bursts of emission. For the case of alumina-ball sliding on an alumina-disk the author found that triboemission large-bursts start in coincidence with alumina-ball pass on the same region of the circular wear-track (Molina et al., 2005).

Triboemission outputs from diamond-scratching of the semiconductor Si show average emission-rates which are relatively constant when computed for different-length periods (e.g., windows). They do not include sporadic but rather repeated large bursts of diminishing intensity. This suggests a characteristics quasi-periodicity for Si triboemission that is not observed for insulators.

2.2 Stochastic analysis of electron triboemission outputs

Triboemission outputs in time domain do not provide enough insight about the triboemission underlying processes and origin mechanisms. In the case of triboemission-outputs the corresponding frequency-domain descriptions can be obtained by count-data post-processing of the discrete count data. This data post-processing can be done for any integer-multiple of the acquisition window-length one. For the purposes of this paper analysis, each considered triboemission output (e.g. each computer-file for a fixed-length of 320 seconds in the 10msec-window) was consolidated in the 40 msec-, 100 msec-, and 250 msec-windows.

For each triboemission output a frequency distribution was then estimated from the frequency of windows with a given number of detected particles, and such frequency-domain description depends on the chosen window-size (e.g. three distributions are computed for each triboemission output). Normalization of the distributions was then carried out by dividing the estimated frequencies by the total number of acquired bins in the record, and the normalized values can be understood as experimental estimations of the probabilities of occurrence for a number of detected particles in the window.

The obtained frequency-domain plots revealed characteristic patterns in the frequency domain, and they suggested that triboemission data might be described by the classic Poisson probability distributions. However, all attempts to fit the classic Poisson distribution to the triboemission data pattern were unsuccessful: a very low-value of the Poisson parameter (e.g., the average rate of occurrence) was needed to obtain a high probability of zero-event (in a window as short as 40mseconds), while a much higher value would be required to match the probabilities of larger number of events. Attempts to fit an exponential distribution also were unsuccessful. Detailed descriptions of such analyses and corresponding statistical testing for “goodness-of-fit” were presented by Molina (2000).

Since neither Poisson nor exponential distributions, which are single-parameter descriptions, were able to match the complexities of triboemission data in frequency-domain, the hypothesis was made that a two-parameter distribution, which can be developed from the convolution of two classic Poisson, may describe the triboemission patterns. The rationale for this hypothesis was that the underlying process could be a two-stage sequence of electron production. A Poisson-type “secondary-emission” component is added to a classic Poisson “primary one”, where the former is function of a “primary-emission” level, and the total observed number of events is the instantaneous sum of primary and secondary events. Such distribution was earlier postulated by Thomas (1949) for "spatially distributed" Poisson variables and it was extended for time series by Matsuo et al. (1984). A corresponding stochastic process (e.g., the Thomas’ process) can be derived if the so-called secondary-event generation is assumed instantaneous, as represented in the block diagram of Figure 5.

Matsuo et al. (1984) also showed that such process is one of the possible generalizations of the classic Poisson point process; if the secondary-event generation cannot be assumed instantaneous, a time delay is assumed for the secondary-event generation, the stochastic process includes a time-invariant linear filter with a non-negative impulse response function h(t) as represented in the following block diagram.

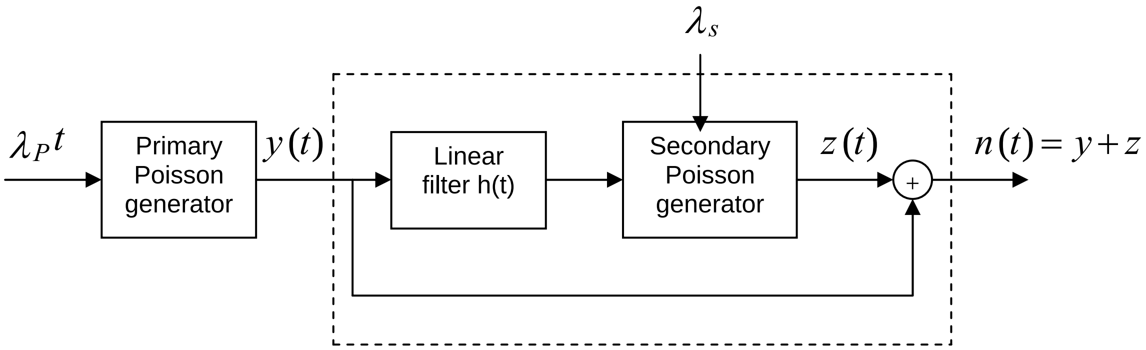

Figure 5. Block diagram of the Thomas' stochastic process. λ_P : "primary-emission" rate, λ_S : "secondary-emission" rate, t: time, n: total number of events, h(t) = λ_P t d(t), for d(t) the Dirac delta function.

In practice, primary and secondary events cannot be distinguished, and the observed convolution of the two sources depends on the used "time-window" (e.g., the acquisition window for experimental data). This Thomas' distribution was found to appropriately describe burst electron triboemission; Figure 6 shows the correspondence between experimental frequency distribution of triboemission data and the computed Thomas's (also called "convoluted Poisson").

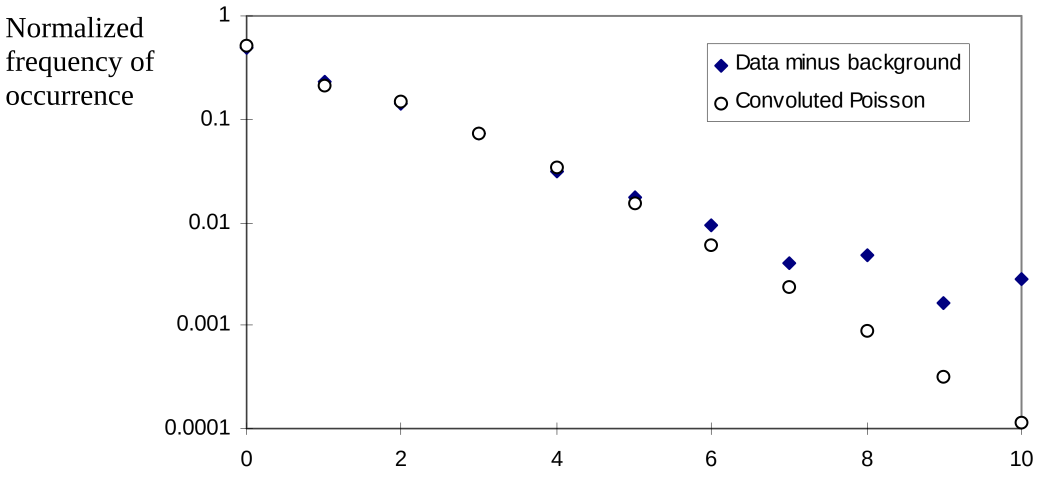

Figure 6. Experimental frequency distribution of triboemission data for diamond-on-sapphire sliding, and of the computed Thomas's (also called "convoluted Poisson")

Testing was done by estimating for each studied output the two independent parameters for the Thomas' distribution using the criterion of minimizing the Chi-square statistics computed from the two sets of probabilities (e.g. from the experimental data and for the proposed distribution) in the 100 ms-window. Since the characteristic decay-time of the largest observed triboemission bursts is of about 100 ms (Molina, 2000), this window-length is adequate for the fit. The same parameter values are used to further extend the testing to each output in the two other considered windows (e.g. 40 and 250 ms-windows). Following

Figure 7 shows the computed Chi-square confidence levels for goodness-of-fit testing of the Thomas' distribution in three windows of representation.

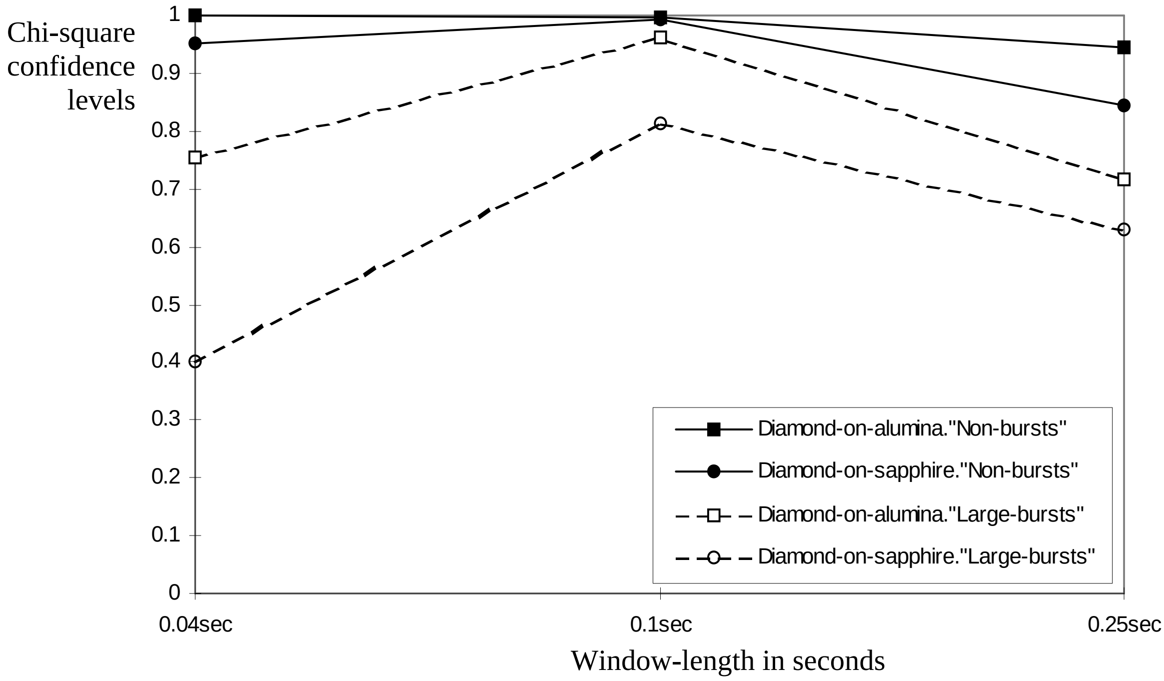

Figure 7. Chi-square confidence for testing of goodness-of-fit of the Thomas' distribution to triboemission data.

The presented analysis shows that the proposed Thomas' distribution tests adequate for characterizing the fraction of triboemitted electrons pertaining to the constant-level of small-burst emission. However, triboemission outputs dominated by large bursts are not well described by this distribution.

Mazilu and Ritter (2004) found that the cumulative distribution of triboemission from diamond scratching of alumina appears to be lognormal, and they suggested it resulted from the underlying distributions of wear debris or debris surface area. Lognormal distributions arise from independent causes acting multiplicative in the system. But triboemission outputs which are dominated by high-bursts seem to be of deterministic origin, and they may not fit any stochastic distribution. Dissado (2002) showed that dielectric breakdown and electrical tree propagation, which are mechanisms that may relate to electron triboemission, occur under conditions of deterministic chaos. This paper following presents an analysis approach of triboemission data on the assumption of underlying deterministic-chaos processes.

2.3 Shannon Spectral Entropy analysis of electron triboemission outputs

Experimental triboemission signal data is sampled for a constant time-window of the shortest length compatible with data acquisition stability (e.g., 10mseconds), such data can be post-processed to be consolidated for longer windows. For the following analysis, each triboemission record is consolidated in the 40msecond-, 100msecond- and 250msecond-window as detailed in previous section 2.2. Data in appropriate time-window may allow estimation of lower frequency variations in the signal. Computation of Shannon's spectral entropy (SSE) was implemented in an ad-hoc developed MS-Excel© spreadsheet. For each considered material system figure 8 presents the computed SSE values for two typical outputs of each tested material (three for diamond-on-Si) in each of the three window lengths.

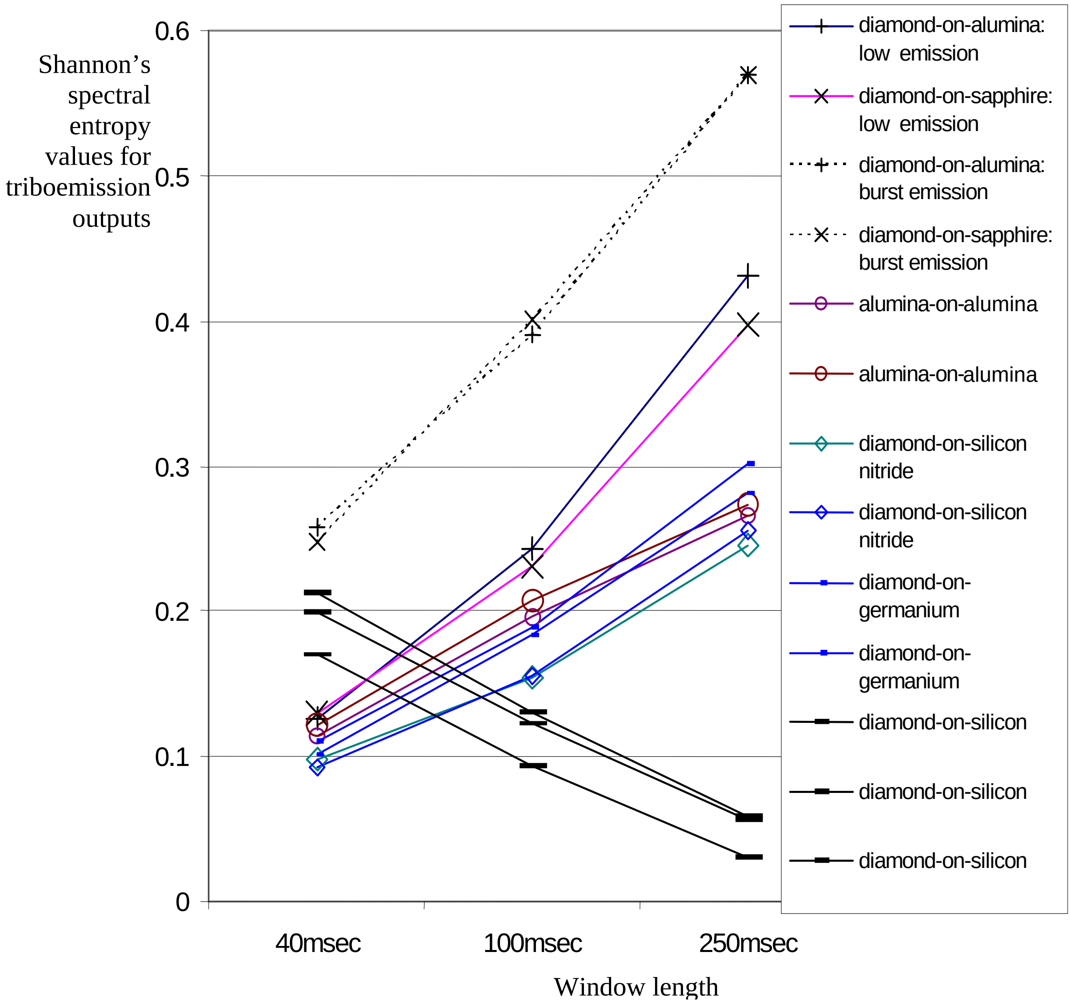

Figure 8. Semi logarithmic plot of Shannon spectral entropy values for different triboemission outputs computed in three window lengths.

Figure 8 shows that all computed values between the lower limit zero (for fully periodical signal) and upper limit 0.6 (for Poisson distribution), and that SEE values depend on the computation window. While there are important differences between SEE values for different material contacts, SEE does not significantly vary within samples of the same material system. Figure 8 also shows that large-burst-type electron-triboemission from scratching of alumina and sapphire yields SSE values higher than those from lower-level constant triboemission from same materials. This result indicates that large-burst-type triboemission outputs are considerably less random, and it suggests that triboemission large-bursts should arise from deterministic processes.

For all tested ceramics the increases of computed SSE from the 40msec- to the 250msec-window indicate larger signal irregularity in longer observation windows, because sporadic triboemission bursts are more likely to occur in longer windows. For the diamond-on-alumina a characteristic burst-length of about 100mseconds was determined by Molina (2000).

For the semiconductor Si the computed SEE values are substantially lower than those for ceramics and they consistently decrease for longer window. This relevant difference is consistent with observed quasi-periodicity for Si triboemission outputs as compared to ceramic ones. In the semi logarithmic plot of figure 8 Si-triboemission SEE values suggest straight-line trends, the extrapolation of them indicates a computation window of about 500 mseconds for a zero SEE value. Although that period is the rotational one of the Si-disk in the experiment (e.g., the length of each repeated pass on the same wear track), the author believes that further data is needed to verify such observation. SEE values for the triboemission from semiconductor Ge do not show the same decreasing trend for longer window, that difference may be related to the substantially lower emission intensity from Ge: the sporadic count can make the use of the SSE analysis not appropriate to detect periodicity, e.g., see Molina et al. (2004); lower Ge count would relate to lower material hardness. Molina et al. also reported the absence of semiconductor triboemission after the contact ceased in comparison to significant post-contact emission from insulators, they hypothesized that absence of surface-charge on semiconductors under vacuum relates to such feature, while substantial surface charge for insulators may be in the origin of their deterministic triboemision large-bursts.

3 CONCLUSIONS

The presented triboemission measurements show electron-emission clearly associated with scratching of ceramics and semiconductors. While triboemission outputs from ceramics include sporadic superimposed large bursts of emission, emission from diamond-scratching of the semiconductor Si does not show large bursts. The presented approach to stochastic analysis of such data shows that a Thomas' distribution tests adequate for characterizing the fraction of triboemitted electrons pertaining to the constant-level of small-burst emission. However, triboemission outputs dominated by large bursts are not well described by this distribution.

An alternative analysis is presented on the hypotheses of deterministic origin versus one of randomness by computing the Shannon's Spectral Entropy of the triboemission outputs in each of three window-lengths. All computed values show in between the lower limit zero (for fully periodical signal) and upper limit 0.6 (for Poisson distribution) and they depend on the computation window. Burst-type electron-triboemission yields SSE values higher than those for lower-level constant triboemission for same ceramics, because sporadic large triboemission bursts are more likely to occur in longer windows. This result suggests that large-burst-type triboemission is considerably less random and that triboemission large-bursts may arise from deterministic processes.

For the semiconductor Si the computed SEE values are lower than those for ceramics, and they consistently decrease for longer window because of periodicity for Si triboemission outputs as compared to ceramic ones. SEE values for triboemission from the semiconductor Ge do not show the same trend because SSE analysis would not be sensitive enough for such sporadic emission count.

Analysis based on SEE is consistent with the testing of fit to known distributions and it is not dependent on the fitting of multiple parameters. Both types of analyses (e.g., based on SEE and on distribution fitting) are sensitive to scaling (i.e., the employed window-length); choosing appropriate windows for computations may show the influence of different burst-features (e.g., if they are of different characteristic length).

The authors believe that the presented type of analysis can be of help for further understanding of electron triboemission features. This approach should also of use for the analysis of experimentally obtained seemingly-random time series. For instance, the author plans to employ these tools to make connections between the phenomenological models of wear and more fundamental theoretical studies that explore the statistical mechanics of non-equilibrium driven systems, e.g., see Gollub and Langer (1999). An alternative entropy metrics has been recently introduced by Tavares and Lucena (2005), for continuous processes measured at finite resolution. Such wavelet-entropy measure is based on an interpolation space of discrete wavelets and is scale-dependent. Entropy values for different components of the wavelet decomposition would reveal deterministic processes at different scales. This metrics, however, has not yet been extended to count-type time series.

4 ACKNOWLEDGEMENT

The author gratefully acknowledge a Faculty Research Committee grant from Georgia Southern University, the use of facilities at Virginia Tech, departments of Mechanical Engineering and of Physics, and fruitful discussions with and encouragement from Drs M.J.Furey, A.L.Ritter and B.Vick of Virginia Tech and Dr. C.Kajdas of the Institute for Fuels and Renewable Energy, Poland.

REFERENCES

Abarbanel, H.D.I., *Analysis of observed chaotic data*, Springer-Verlag New York, Inc., NY, USA, 1996.

Alligood, K.T., Sauer, T.D. and Yorke, J.A., *Chaos: an introduction to dynamical systems*, Springer-Verlag New York Inc., N.Y., USA, 1996.

Dickinson, J.T., Jensen, L.C. and Jahan-Latibari, A., Fracto-Emission: The Role of Charge Separation, *Journal of Vacuum Science Technology*, A2 (2): 1112-1116, 1983.

Dissado, L. A., Deterministic Chaos in Breakdown. Does It Occur and What Can It Tell Us?, *IEEE Transactions on Dielectrics and Electrical Insulation*, 9 (5): 752-762, 2002.

Furey, M.J., Kajdas, C., Kempinski, R. and Tripathy, B., Action Mechanism of Selected Vinyl Monomers under Boundary Lubrication of an Alumina-on-Alumina System, *Lubrication Science*, 10: 3-25, 1997.

Gollub, J.P. and Langer, J.S., Pattern formation in nonequilibrium physics, *Rev. Mod. Phys.*, 71: 396–403, 1999.

Johnson, R.W. and Shore, J.E., Which is the Better Entropy Expression for Speech Processing: -S log S or log S?, *IEEE Acoustic and Speech Signal Processing*, ASSP-32: 129-137, 1984.

Kajdas, C., Furey, M.J., Ritter, A.L. and Molina, G.J., Triboemission as a Basic Part of the Boundary Friction Regime: A Review, *Lubrication Science*, 14: 223-254, 2002.

Kim, M., Langford, S.C. and Dickinson, J.T., Electron and Photon Emission Accompanying the Abrasion of MgO with Diamond, *Tribology Letters*, 1: 147-157, 1995.

Matsuo, M., Teich, M.C. and Saleh, B.E.A., Poisson Branching Point Processes, *Journal of Mathematical Physics*, 25: 2174-2185, 1984.

Mazilu, D.A. and Ritter, A.L., Statistical Characteristics of Vacuum Triboemission from Abrasion of Alumina, *Tribology Science and Application,* M.A. Herman (editor), CUN PAN Warszawska Drukarnia Naukowa PAN Publishers, Warsaw-Vienna, 232-250, 2004.

Molina, G.J., *Triboemission From Ceramics: Charge Intensity and Energy Distribution Characterizations*, PhD. Dissertation, Dept. of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA, 2000.

Molina, G.J., Furey, M.J., Ritter A.L. and Kajdas, C., Triboemission from Alumina, Single Crystal Sapphire, and Aluminum, *Wear*, 249(3-4): 214-219, 2001.

Molina, G.J., Furey, M.J., Ritter, A.L. and Kajdas, C., Frequency Analysis and Modeling of Charged-Particle Triboemission from Ceramics, *Wear*, 255(1-6): 686-694, 2003.

Molina, G.J., Furey, M.J. and Kajdas, C., On the Triboemission from Selected Ceramics and Semiconductors, *Proc. of the 11th Nordic Symp. on Tribology NORDTRIB 2004*, Oslo, Norway, CD Rom, 2004a.

Molina, G.J., Mazilu, D.A., Furey, M.J. and Kajdas, C., On Triboemission from the Sliding Contact of Si and Ge, *The Annals of University "Dunarea De Jos" of Galați, Romania*, VIII (Tribology): 22-29, 2004b.

Molina, G.J., Furey, M.J., Kajdas, C. and Steika, N., On the Mechanism of Electron Triboemission from Ceramics, *The Annals of University "Dunarea de Jos" of Galati, Romania*, VIII (Tribology): 17-23, 2005.

Molina, G.J., Furey, M.J. and Kajdas, C., Charged-Particle Triboemission, Tribocharging and Work Function Change from Scratching of Insulators, *Proceedings of the 30th Annual Meeting of The Adhesion Society*, February 18-21, 2007, Tampa Bay, FL, USA, 138-140, 2007.

Nakayama, K., Bou-Said, B. and Ikeda, H., Tribo-Electromagnetic Phenomena of Hydrogenated Carbon Films. Tribo-Electrons, -Ions, -Photons, and –Charging, *Transactions of the ASME Journal of Tribology*, 119: 764-768, 1997.

Nakayama, K. and Fujimoto, T., The Energy of Electrons Emitted from Wearing Solid Surfaces, *Tribology Letters*, 17 (1): 75-81, 2004.

Pincus, S.M., Approximate Entropy as a Measure of System Complexity, *Proceedings of the National Academy of Sciences USA*, 88: 2297-2301, 1991.

Pincus, S. and Huang, W-M., Approximate Entropy: Statistical Properties and Applications, *Communications in Statististics-Theory and Methods*, 21 (1): 3061-3077, 1992.

Shannon, C.E. and Weaver, W., *The Mathematical Theory of Communication*, University of Illinois Press, Chicago, IL, 48-53, 1949.

Tavares, D.M. and Lucena, L.S., Entropy analysis of stochastic processes at finite resolution, *Physica A*, 357: 71-78, 2005.

Thomas, M., A Generalization of Poisson's Binomial Limit for Use in Ecology, *Biometrika*, 36: 18-25, 1949.