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Arc root dynamics in high power plasma torches – Evidence of chaotic behavior

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Abstract. Although plasma torches have been commercially available for about 50 years, areas such as plasma gun design, process efficiency, reproducibility, plasma stability, torch lives etc. have remained mostly unattended. Recent torch developments have been focusing on the basic understanding of the plasma column and its dynamics inside the plasma torch, the interaction of plasma jet and the powders, the interaction of the plasma jet with surroundings and the impingement of the jet on the substrate. Two of the major causes of erratic and poor performance of a variety of thermal plasma processes are currently identified as the fluctuations arising out of the arc root movement on the electrodes inside the plasma torch and the fluid dynamic instabilities arising out of entrainment of the air into the plasma jet. This paper reviews the current state of understanding of these fluctuations as well as the dynamics of arc root movement in plasma torches. The work done at the author's laboratory on studying the fluctuations in arc voltage, arc current, acoustic emissions and optical emissions are also presented. These fluctuations are observed to be chaotic and interrelated. Real time monitoring and controlling the arc instabilities through chaos characterization parameters can greatly contribute to the understanding of electrode erosion as well as improvement of plasma torch lifetime.

Keywords. Thermal plasmas; arc root; instabilities; chaos; electrode erosion; dynamic characteristics.

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1. Introduction

Despite the intense developments in the area of arc plasma sources and processes, there exists very little knowledge base about the basic plasma phenomenon involved in building these devices. Consequently, the respective plasma systems are plagued with short device lifetime, poor efficiency, unreliable performance and uncontrolled erosion of electrodes. Two of the major causes are currently identified as the fluctuations arising out of the arc root movement on the electrodes and the fluid dynamic instabilities in the plasma jet. These are factors responsible for severe degradation in the quality of the final product through incomplete or non-uniform processing as well as deterioration in device efficiency. A detailed investigation to explore the basic nature of arc root movement could help in optimizing electrode life, improve process efficiency as well as maintain electrode thermal integrity [1].

Modeling a plasma jet is always an easy, cost effective, time saving, alternative approach to get design criteria of a torch with best performance for specific applications. However, a comprehensive model of the plasma jet incorporating all physical phenomena involved in the process is not possible unless one completely explores the nature of transient phenomena occurring inside the plasma torch. Therefore, no sensible comparisons of computation with experimental data have been possible so far [2].

The early attempts to understand the basic physics and chemistry of thermal plasmas vis-a-vis the device engineering focused on the basic transport equations of the field free plasma jet which were solved through finite difference techniques. Very few works on the plasma column actually include the electromagnetic, thermal and gas dynamic effects [3–5]. The complexities arise due to lack of realistic boundary conditions, non-equilibrium conditions at the electrodes and surface conditions at the arc attachment zone. Therefore, the observed effects of strong entrainment of ambient cold gas, whipping and surging type of movements of arc mainly caused by axial and circumferential motion of the arc root seen through shadowgraphs, CARS spectroscopy and time resolved photographs were not predicted exactly. The fluctuation spectrum shows a frequency range of 2–10 kHz, depends on the plasma gas and is known to affect torch performance and process quality.

2. Dynamics of arc root movement

In arc plasmas, both the arc column and the arc root are extremely important from stability point of view. The axial or the vortex gas flow, electromagnetic forces (JXB) and thermal energy transport processes govern the structure and shape of the electrode attachment column, which is continuously being distorted. These tend to push the arc loop and lengthen it towards downstream of the spot and towards the opposite wall. Breakdowns occurring through the cold layer surrounding the arc generate highly transient variations in arc voltage, plasma flow, temperature, velocity, optical and acoustic emissions. The electrode surface also affects motion of the arc root as it slides smoothly over a new surface but gets anchored on pitted surfaces (it takes about 30–60 minutes for craters to be created) whence the stagnation mode dominates with upstream and down stream re-arcings. The interactions of the arc with the cold electrode results in three characteristic modes of interactions [6] (figure 1). The mode 2 is a large scale arc to wall shunting. The mode 4 is a small scale shunting arising due to the arc column instabilities near the arc root, arc spot shifting radially downstream giving rise to shunting. The third mode labeled 3 is due to the low magnitude undulations of arc voltage at much higher frequencies. The mode 2 and 4 give rise to saw tooth type fluctuation of arc voltage with upstream re-strike being characterized by lower voltage minimum and high jump voltage as contrasted to downstream shunting. Figure 2 depict a typical voltage waveform with U and D indicating upstream and downstream shunting. The period between successive jump is the spot or root residence time. A statistical study over a large number of recorded voltage signals [11] depict that the upstream strikes are more destructive and show almost 3 to 4 times spot lifetime as compared to the downstream re-strikings. The highest life times correspond to lowest voltage minima. This indicated that erosion must be a maximum for a short arc column.

The arc serves as a sensitive measure of the internal state of the plasma device. The voltage across and the current through the arc are related to plasma temperature, system geometry, ionic species, electrode temperature, arc target material, ambient conditions and other system parameters. As a result, the fluctuation in position of arc root in a plasma torch gets manifested thorough three main signals, namely voltage, optical and acoustic

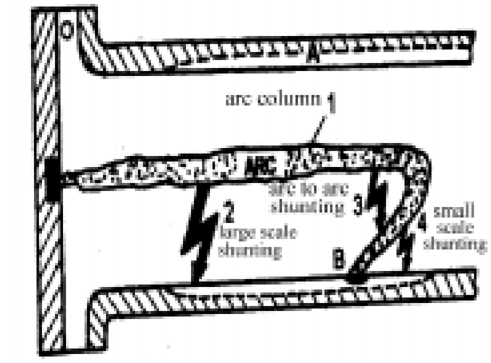

Figure 1. Arc shunting schematic [10].

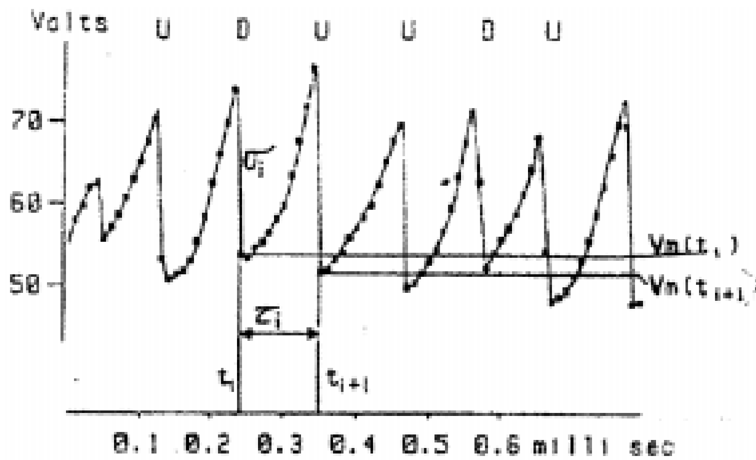

Figure 2. Schematic of the temporal evolution of arc voltage [2].

signals. Moreover, due to the coupled non-linear interdependence of the system variables, each of these signals is interrelated to the fluctuation in arc root position and all of them will exhibit similar nonlinear behavior. It has been recently shown [17] that these signals not only reflect the arc root fluctuations but also show chaotic behavior. Furthermore, experiments have clearly shown that the three signals i.e. voltage, optical and acoustic signals show definite dimensional correspondence in phase space.

3. Summary of earlier results

Very few of attempts have been made in literature to study fluctuation of arc root in a plasma torch [2,8]. The most interesting one is by Paik *et al* [2] who used Steinbeck voltage minimum principle to determine the arc root position on the electrode. Broadly, the major approaches to the study of arc fluctuations and dynamics can be categorized in to (a) the study of electrode erosion, (b) dynamic arc characteristics and (c) chaotic dynamics.

3.1 *Arc root movement and electrode erosion*

Electrode erosion in high power plasma torches has been seen to be intimately related to arc root dynamics. Experiments have been reported by Szente *et al* [9], Brillhac *et al* [10,11], Coudert *et al* [7] and Dorier *et al* [12] linking electrode erosion from cooled copper electrodes as functions of arc parameters. Electrode erosion follows an inverse power law in arc root velocities i.e. $e \; \alpha \; v^{-n}$, where n varies from -2 for molecular gases to -0.6 for argon. Use of traces of molecular gases increase erosion due to catalytic effect on the surface. Location of the erosion zone and its extent also depends on the arc velocity. The flow rate of plasma gas simultaneously controls the stretching of the arc and the thickness of the cold boundary layer. These two mutually opposing effects result in a weak dependence on the erosion. On the other hand, increasing the diameter of the plasma tube, increases the average spot lifetime and increases the voltage jump amplitudes appreciably. Consequently, the erosion zone expands and is pushed away from the opposite electrode. Magnetic fields have often been used to control arc root movements. The deflecting/rotating and stabilizing magnetic field affects the arc spot residence time favorably but increases electrode erosion due to the focusing of current lines. Zhukov [6] analysed the interaction of solenoid magnetic fields with arc root and showed that the magnetic fields and the coil position could be manipulated so that the arc spot could be made to move along the electrode length reducing erosion.

Increase in arc current reduces the arc spot lifetime. Simultaneously however, the arc diameter increases making shunting more frequent. The arc remains confined to a small zone with very small voltage jumps. Coudert *et al* [7] observed an average reduction in the spot life time by a factor of four on doubling the current from 300 A to 600 A. The erosion zone shifted nearer to the opposite electrode. For new electrodes and noble gas plasmas fluctuations reduce drastically. As the electrode is used more and more, stagnation triggers fluctuations.

Increasing gas swirl is seen to increase the voltage jumps during restrike with faster oscillations riding on the saw tooth. This is mainly due to the gliding orbital motion of the spot and efficient cooling of column fringes. The reported erosion rates (100–600 A) varied from 1 microgram per Coulomb to about 100 micrograms per Coulomb. The overriding influence of electrode diameter D, gas flow G and current I on the arc spot residence time τ are expressed through dimensional analysis as the following.

$$\bar{\tau} \approx K \cdot \frac{D^2}{(G \cdot I^2)^{1/3}},$$

where K defines the nature of plasma gas used.

3.2 *Arc dynamic characteristics*

Research on the dynamic characteristics of arc is extremely recent [6,7,10–12,] and is not as well defined as the static characteristics. The time series and frequency spectrum of the arc voltage, optical emission and acoustic emission are the parameters studied along with the arc spot motion. Power spectra show frequencies in the 1–10 kHz range which show variations under differing plasma gas conditions, flow rates, vorticity with appearance of fresh peaks in the frequency spectra. Correlations between signals of voltage and optical radiation gives the arc velocity V. Arc rotation is measured by optical means [13]. The dynamic characteristics is expressed through non-dimensional correlations which are easily scalable.

Experimentally, the voltage and current spectra are noisy with frequency peaks shown around 4–8 kHz. The frequency increased with current as well as the gas flow. A study of the synchronized signals of arc voltage, arc current, power level, plasma radiation, derivative of power level and acoustical pressure showed that:

(i) A strong correlation exists between the electrical power fluctuations showing the characteristic oscillations of the arc voltage and the current signals with the optical signal. This correlation is used as diagnostic tool to measure jet velocity.

(ii) A strong correlation exists between the time derivative of the electrical power and the acoustic fluctuations. The low frequency component disappears completely in both of these. This made it clear that the sound source in a plasma torch is connected to the arc attachment and restrike phenomena at the electrode wall.

Some of the similarity criteria for dynamic as well as static characteristics of arc plasma torches are given below.

$$Sf = 0.004 Si^{-0.3136}\,\mathrm{Re}^{-0.3541}\,Sg^{0.705},$$

where Sf, Si, Re and Sg are frequency, energy, Reynold's and geometry numbers respectively.

The spot rotation velocity

$$V_{\mathrm{rotation}} = 1620\left(\frac{JB}{PD}\right)^{0.5}\cdot\left(\frac{\delta_{e\ \mathrm{lg}\ ap}}{d_{el}}\right)^{-0.3}\mathrm{e}^{-0.04V_{\mathrm{blow}}},$$

$T_0 = 8600\ K \Leftrightarrow \alpha = 1\%$, α is the degree of ionisation. $Sf = (fd_{el}^2\sqrt{\sigma_0\mu_0})/I$, f is the characteristic frequency, d is electrode diameter and I the arc current. $Si = I^2/Gd\sigma_0 h_0$, G indicates the mass flow rate of plasma gas. $\mathrm{Re} = G/\mu_0 d$. $Sg = (l_a d_c/l_c d_a)$, l and d indicate electrode length and diameters respectively. σ_0, μ_0, h_0 are electrical conductivity, viscosity and enthalpy of the plasma at a reference temperature $T_0 = 8600$ K.

3.3 *Nonlinear behavior and evidence of chaos*

The concept of using chaotic response of stabilized arc plasmas to study and control arc dynamics is an extremely recent idea [17] though the earliest hint came from the data of Paik *et al* [2]. In their study of arc root fluctuations the authors overlooked evidence of a typical Fiegenbum scenario of period doubling leading to chaos. King *et al* [14], Lago [15] reported chaotic response in AC electric arc furnaces where the low frequency portion of the arc voltage signal was analysed in great detail for power spectra, correlation dimension, phase space reconstruction and the Poincare' section. The phase space reconstruction

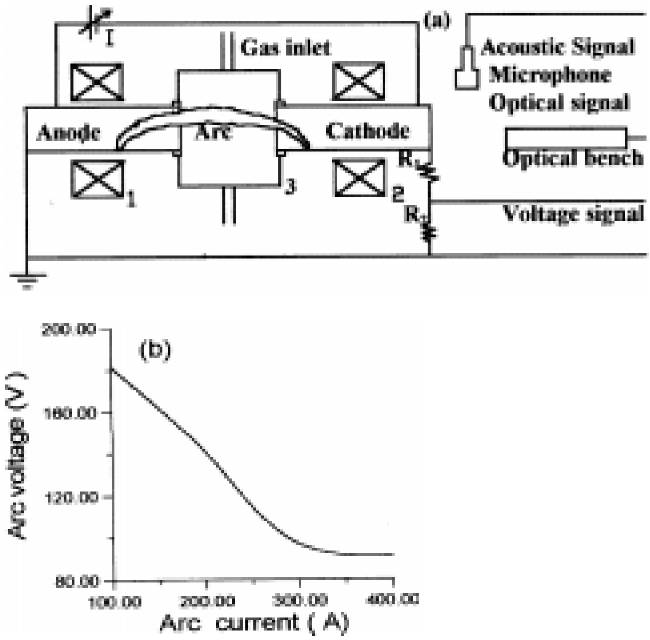

Figure 3. (**a**) Schematic of experimental setup [1,2 magnetic coils; 3 vortex chamber]. (**b**) Discharge voltage-current characteristic.

of the lagged time series showed a strange attractor with two distinct lobes corresponding to motion during each half cycle. Recently in 1999 Carrillo [16] analyzed electric arc furnaces as a highly varying nonlinear load in a nonlinear deterministic modeling and found that fluctuations in plasma welders can be modeled using chaotic dynamics. More recently, experiments at our laboratory [17] showed conclusively the evidence of chaotic response in high power DC plasma devices.

4. Experimental system

The typical experimental system for the study of arc root dynamics in our laboratory is shown in figure 3. It consists of a high power (>100 kW) hollow electrode plasma torch shown in figure 3a with typical voltage-current characteristic shown in figure 3b. The torch was designed and fabricated at the laboratory. The choice of experimenting with a hollow electrode plasma source was due to the many advantages it offers. Firstly, it is possible to use any kind of plasma gas in such torches. Secondly, the electrodes are easily exchangeable and it is easy to study vortex and magnetic stabilization. However, most importantly, we are in the process of developing air operated hollow electrode torches operating at high power for dedicated end uses like plasma melter and gas heaters.

The torch comprises of two hollow electrodes made up of electrolytic copper and a vortex chamber, posited centrally and isolated electrically from the cathode and the anode. The vortex chamber, made of copper, mainly functions as an intermixing chamber for the plasma generating (plasmogen) gases and is specially designed to introduce adequate vorticity to the gases. The other components consist of two constant current power supply units for igniting (rating 10 kVA) and sustaining (rating 500 kVA) the arc, power supplies for stabilizing magnets, control desk, water cooling system, supply system for plasmogen gas.

The static measurements consists of time averaged current, arc voltage, gas flow and water flow meters. In addition, a calorimetric set up measured the heat loss to the electrode walls. Fluctuation measurements were made on four physical parameters namely the arc voltage, the arc current, optical luminosity and the acoustic pressure. The optical luminosity measurement was performed with an optical bench collecting radiation emitted at a given point from the plasma jet and transporting the light to a photo multiplier set up. The acoustic fluctuations were measured with a large bandwidth (1–40 kHz) microphone mounted near the plasma jet. The arc voltage signal was taken from directly across the arc and current signals were recorded using a series shunt. A multi-channel digital oscilloscope (12-bit digitizer, maximum sampling rate $= 10^7$ samples/s) was used to acquire the data. In each case a total of twenty thousand samples were taken. Voltage (v), optical (O), and acoustic (X) signals presented here refer to a.c. components only. $\Phi(n)$ is the nth sample of signal Φ. Arc is initiated through a hf igniter and stabilized to form plasma jets emanating from ends of both cathode and anode. Stabilization is done through energy transfer to the cold gas at the wall constricting the arc jet, concentrating the energy flux and simultaneously localizing the jet in configuration space. Two flange cooled solenoid coils producing a centerline field of 200–500 Gauss (controlled through solenoid current) are mounted on both the electrodes to provide stabilizing magnetic field. Argon is used as plasmogen gas in all the cases reported, though the system was operated in air also. Optical signal refers to the intensity of total optical output. Major problem in operating high power arc is its stability. In our case the arc was not stable below 100 A and system was thermally over stressed above 400 A. Data were collected over a large number of runs. All observations reported here are restricted within this operating regime.

5. Results and discussions

The plasma torch worked in the re-strike mode. We examined the voltage, acoustic and optical signals (the three basic signals directly or indirectly related to the behavior of arc root), their power spectra and typical attractors presented by such signals in phase space. All the observed signals show apparently random real time behavior, continuous power spectra and a typical attractor structure observed in chaotic systems. Though both chaotic and completely random systems show apparently random real time behavior and continuous power spectra, the phase portraits differ considerably. A random system never shows any definite phase portrait in phase space but a chaotic system does. The other investigating tools to distinguish a chaotic system from a random system are Lyapunov exponent and dimension. The first one gives exponential rate of divergence of nearby orbits in phase space, a unique stretching property exhibited only by chaotic systems. The second one gives low fractal dimension of attractor in case of chaotic system. Since a truly random phenomenon is an infinite dimensional process, a random system can never show low fractal dimension. Finally a comparative study of the dimensionality of all the signals (recorded simultaneously) shows correspondence of physical phenomena.

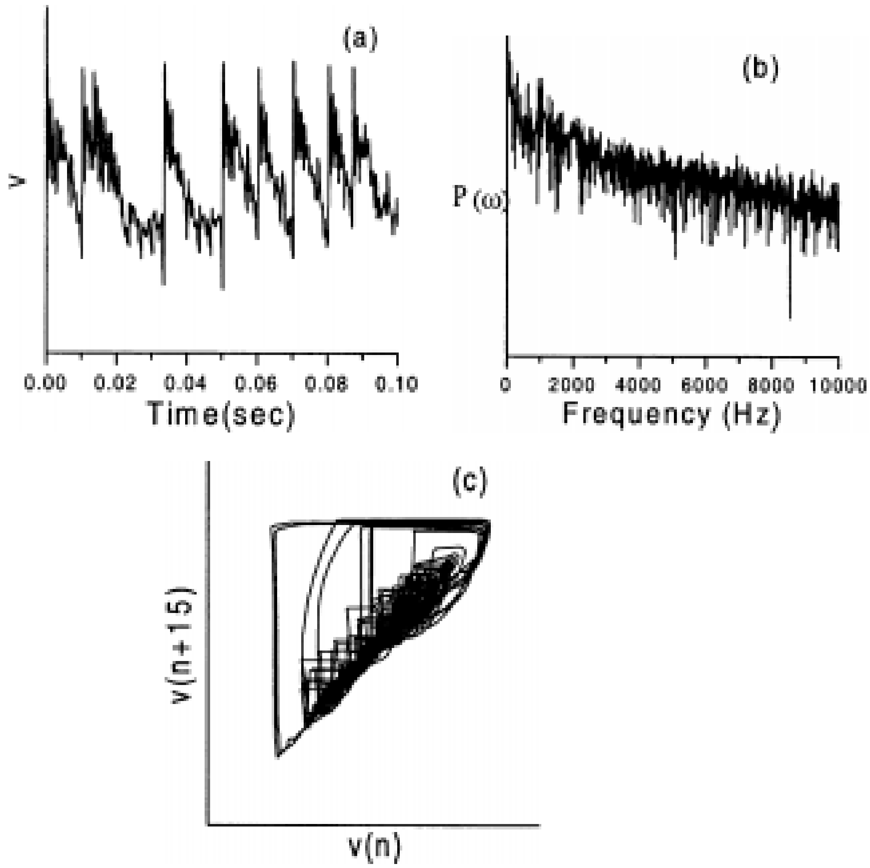

Figure 4. (**a**) Voltage signal, (**b**) power spectra, (**c**) attractor structure. Other discharge parameters are: flow rate of argon $(G_{\mathrm{Ar}}) = 100$ liter per min. (lpm), flow rate of air $(G_{\mathrm{air}}) = 40$ lpm, arc current $(I) = 300$ A, sampling interval $(\Delta t) = 5$ μs. $P(\omega) =$ spectral amplitude at frequency ω.

5.1 *Voltage signal*

The fluctuation in arc voltage recorded from the system showed a reverse saw-tooth waveform with sudden and irregular amplitude jumps (figure 4a). The upstream and down stream restrike modes are self evident. Since the anode is grounded, the gradual and irregular fall in voltage towards more negative value is observed. As the current paths get lengthened, intermixing of relatively cold gases from adjacent layers as well as the turbulent conditions heat and ionise the gas causing formation of plasma bubble near the arc root. In course of time, size of this bubble increases and the gas dynamic drag disconnects it from the arc. Minimum energy consideration then favors a sudden re-striking of the arc to an upstream position resulting in sudden jump in voltage signal towards less negative value after the gradual fall in voltage. A detailed mathematical description on various interacting forces are worked out on the basis of work carried out by Collares *et al* [18].

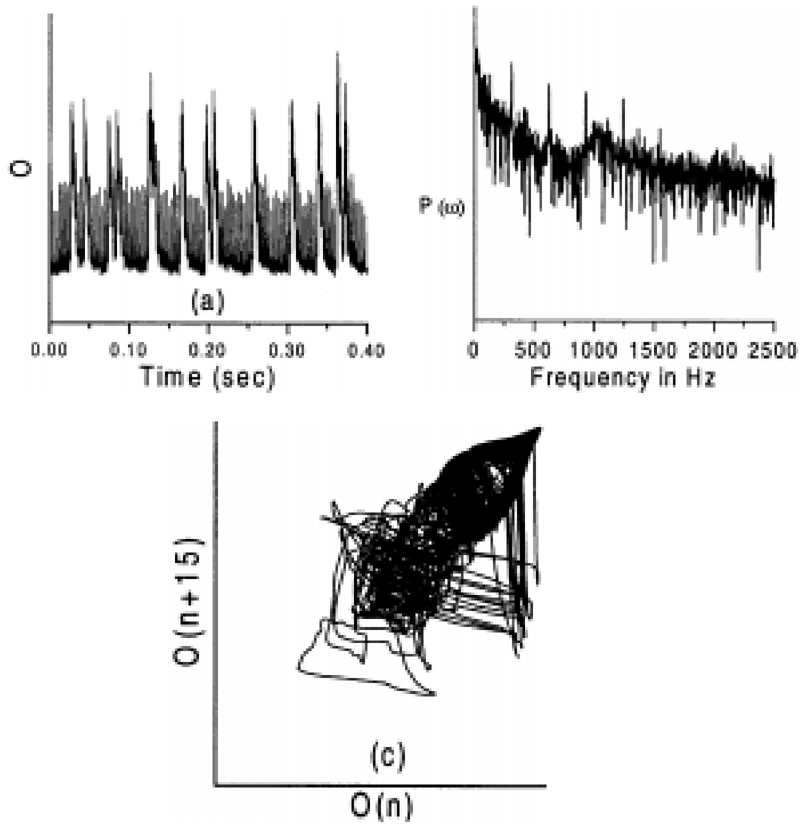

Figure 5. (**a**) Optical signal, (**b**) power spectra, (**c**) attractor structure. Discharge parameters are: $G_{\rm air} = 100$ lpm, $G_{\rm Ar} = 40$ lpm, $I = 300$ A, $\Delta t = 20\ \mu$s.

Evidence of plasma bubble formation has been seen by us from the simultaneous recording of arc voltage and optical signals; every jump in voltage signal is associated with a peak in photo-multiplier output which corresponds to formation of a bright plasma bubble. Power spectrum of the voltage signal (figure 4b) is broad band and continuous. Typical attractor obtained from such signals is presented in figure 4c.

5.2 *Optical signal*

The intensity of total optical out put from the system is proportional to the net power fed to the discharge. For a constant current source, the optical fluctuation follows the voltage. Typical time series for optical signal obtained in the experiment is shown in figure 5a. Power spectra is broad band and continuous (figure 5b). Prominent peaks at 300 Hz and its harmonics are due to ripples at this frequency present in the three-phase

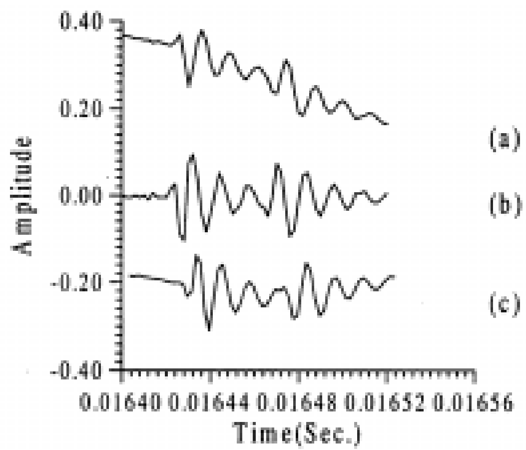

Figure 6. (**a**) Voltage signal, (**b**) derivative of the voltage signal, (**c**) corresponding acoustic signal.

power supply. Though the ripple in supply is negligible compared to the power supplied, it is getting reflected in this signal. Typical attractor obtained for this signal is shown in figure 5c. Evolution of the attractor shows all aspects observed in other chaotic systems.

5.3 *Acoustic signal*

The origin of acoustic noise is the vibration due to pressure fluctuations in the flowing plasma. The time rate of change of the electric energy pumped in to the charged particles and the rate of collisional transfer to the neutrals decide the characteristics of the acoustic fluctuations with the amplitude of acoustic disturbance being proportional to the time derivative of electric power. In figure 6, curve (a) depicts part of a typical voltage signal recorded from the system. Curve (b) shows the numerical derivative of this voltage signal and the curve (c) depicts the corresponding acoustic signal. The correspondence is obvious. Figure 7a presents a typical acoustic signal recorded from the system. Continuous broad band power spectra and typical attractor observed for this signal is shown in figure 7b and 7c respectively.

5.4 *Lyapunov exponent and dimension*

Quantitative characterization of chaotic dynamics is provided by the Lyapunov exponents [17] The sign of the Lyapunov exponents provide a qualitative picture of the system dynamics. Unless a system is chaotic, it will always show most positive Lyapunov exponent (λ_1) either zero or negative. Using Wolf's fixed evolution time program [20], it has been found that all the signals presented here provides positive Lyapunov exponent definitely. Evolution of λ_1 for the attractor of figure 2c is presented in figure 8a. Least square fit of the data where λ_1 is almost stationary provides $\lambda_1 \simeq 7.5$ bits/ms. This definitely shows that the system is chaotic.

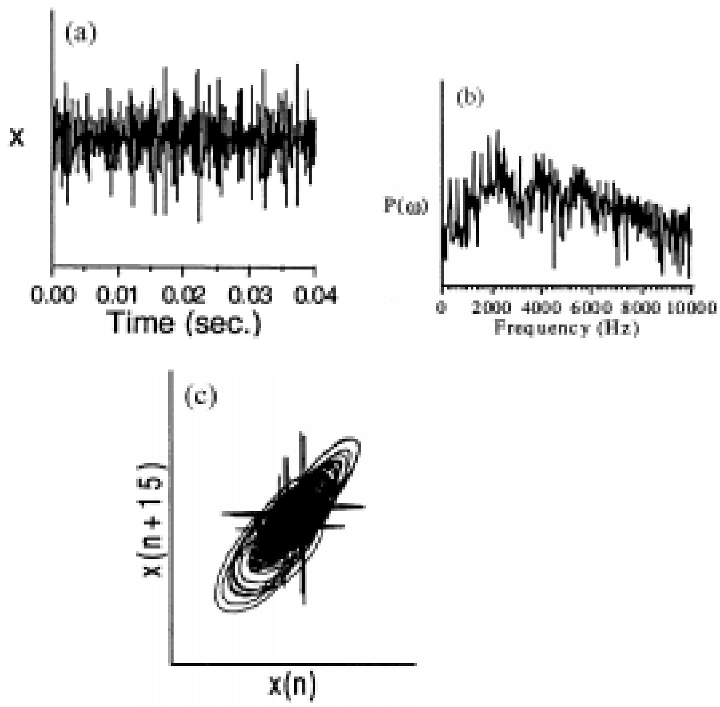

Figure 7. (**a**) Acoustic signals, (**b**) corresponding power spectra, (**c**) attractor. Other discharge parameters are $I = 200$ A, $G_{\mathrm{Ar}} = 120$ lpm, $G_{\mathrm{air}} = 0$, $\Delta t = 2$ μs.

The phase space dimension of a dynamical system gives information on the minimum number of state variables required to describe the dynamics of the system. A number of statistical measures is available for dimension such as capacity dimension (D_{cap}), information dimension (D_I), correlation dimension (D_C) etc. Among all these, correlation dimension is most widely used. Computed dimension for a random signal, increases linearly with increase in dimension of state space in which computation is done. In fact the computed dimension just becomes equal with dimension of the state space. Whereas the computed dimension for chaotic, quasi-periodic and periodic systems remains invariant under change in dimension of state space (provided applied state space dimension is sufficiently higher than the actual dimension of the attractor, so that proper unfolding of the attractor can take place). Chaotic signals can be easily distinguished from quasi-periodic and periodic signals using the fact that the computed dimension is always fractal for a chaotic signal whereas it is integer for the other two.

In figure 8b computed D_C is plotted against dimension of state space in which computation was done for the attractor of figure 4c and for a random noise signal. The dimension of embedding state space was varied from 2 to 8. The random signal D_C increases almost linearly with dimension of the state space. Whereas for the experimental signal, after state space dimension four, D_C reaches a stationary level and provides a dimension of 2.3. This fractal dimension together with positive Lyapunov exponent proves the present system to be definitely chaotic.

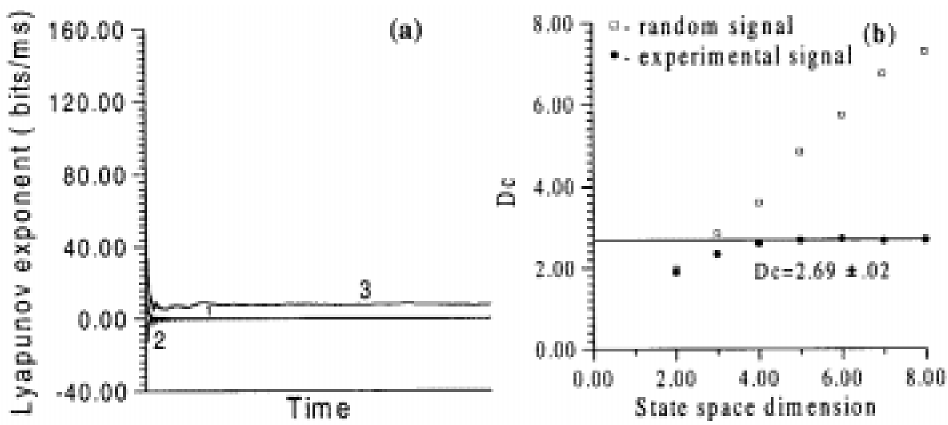

Figure 8. (**a**) Evolution of Lyapunov exponent (1-random noise, 2-sine signal, 3-signal of figure 4a), (**b**) correlation dimension for the attractor of figure 4c and a random noise signal.

6. Summary and conclusion

Prime foci of present research and development efforts in thermal plasma technology include improvement and optimization of plasma torch performance, study of plasma jet instabilities, reduction of electrode erosion, improvement of device lifetime, improvement in quality of plasma processing work and more realistic modeling of plasma jet. Further progress in each of these fields are directly or indirectly hampered due to lack of complete picture of fluctuation of arc root in corresponding plasma generating devices The studies on arc root dynamics have distinctly pointed to the increasing complexities in an arc under (a) introduction of molecular or reactive gas, (b) increased current, (c) increased flow rate or vorticity, (d) increased arc column length, (e) complex, irregular, pitted surface or system geometry. This results in the power spectra becoming noisy, the time series becoming complicated and most of all, the amount of stretching in phase space for the system or the Lyapunov exponent varying dramatically. A stable smooth running argon arc may show a Lyapunov exponent of -0.96 and an unstable nitrogen arc may show exponent of 17.71. With the increase in complexity, the attractors become broad and the small scale dynamics become more scrambled. The dimension increases and the Lyapunov exponent also increases. However, The correlation dimension is low indicating slow loss of information and possibility of real time control.

The future of arc root dynamics lies in direct correlation between electrode erosion and plasma jet instabilities with the recorded transients. This will involve detailed experiments involving high speed imaging of the arc in real space, imaging of the electrode surface, and high speed signal acquisition. The different types of plasma i.e. hollow cathode, solid cathode torches in transferred and non-transferred mode must be studied separately. Theoretical tools for spectral analysis, modeling of arc root movement, turbulence in plasma jets must be developed to predict the experimental data. The concept of chaos control in arc jets is still too vague. This needs to be further crystallized.

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