Institute of Thermomechanics
Prague, Czech Republic

DEPARTMENT OF ELECTROPHYSICS

Thermal plasma jet stability estimations by correlation dimensions – comparison with FFT and wavelet analysis

J. Gruber, J. Hlína, J. Šonský

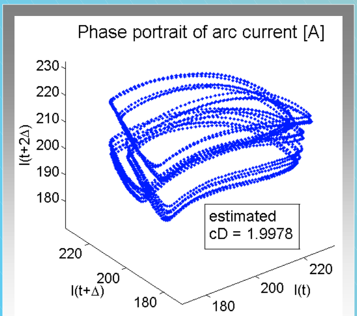
Institute of Thermomechanics AS CR, v. v. i., Dolejškova 5, 18200 Praha 8, Czech Republic

MOTIVATION

Thermal plasma jets are used for variety of industrial applications (including plasma chemistry, plasma spraying, plasma etching, waste treatment, synthesis of new materials and layers, etc.). Better understanding the dynamics of plasma jets is crucial for reproducibility and improved control of these applications. Here we present results of plasma arc stability estimations based on arc current records. Following our previous results based on **Fourier analysis** and **wavelet analysis**, we compare these two methods with **correlation dimension estimation** and point at some connections.
All the methods (correlation dimension estimation, wavelet analysis and FFT) are based on analysis of the arc current records in the experimental plasma torch device.

ESTIMATION OF "cD"

Correlation dimension (**cD**) refers to one of the generalized dimensions of fractal-like structures. In our case the "structure" is the **phase portrait** (in the reconstructed phase space) of the arc current dynamics.
We **divided each record** into subsequent chunks, 2500 points each, and tried to **estimate cD for each chunk**. Correlation dimension was estimated by method based on *Grassberger-Procaccia algorithm*. A (phase portrait) **point is chosen pseudorandomly** and then we calculate **number of points inside the hypersphere** surrounding this point. This is **repeated for increasing hypersphere diameters**, many central points and compared for different dimensions of the embedding space. The **number of the points grows exponentially** with hypersphere diameter in general. **Exponent** of this increase **is** our **estimated** correlation dimension **cD**.



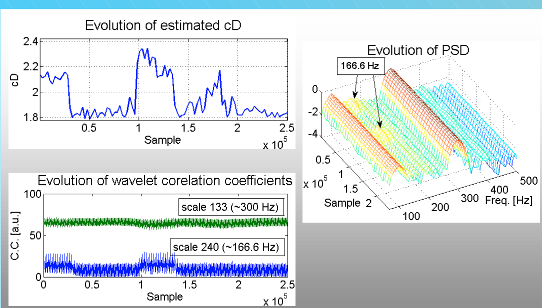
Sample phase portrait
(chunk of 2500 points, Δ=1.25ms)

FFT and WAVELETS

Spectral density calculated by the Fourier transform was also estimated for different parts of the record separately.
Chunks used for cD estimation are too short for reasonable Fourier analysis, so we used longer parts of data, 8192 points each.
Wavelet correlation coefficients change continuously during the whole record, so we do not have to calculate them extra for each chunk..

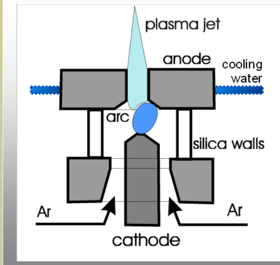
PEAKS AT FREQUENCY 166.6 Hz

Even within one record there are **parts** where estimated **cD** is quite **below 2**, parts where estimated cD is quite **above 2** and **transition parts** where cD changes substantially. Although these parts **differ in spectra**, the difference is not very clear. Only remarkable difference in PSD is the **peak at frequency 166.6 Hz in the unstable (cD>2) part**, which is not present in other parts of the record.
Wavelet analysis at the corresponding scales show this correspondence very clearly. Oscillations of **scale 240 points** (~166.6 Hz) are **suppressed** in the parts where **cD**<2.



Concurrent evolution of analyzed values (argon flow rate 0.5 g/s).

EXPERIMENTAL ARRANGEMENT



Plasma torch schematics

Plasma jet is generated by the experimental vertically oriented plasma torch device at atmospheric pressure. We use argon as the working gas.
Arc length is **5 mm** and the nozzle diameter is **6 mm**. Mean d.c. arc current was set, depending on experiment, **100 - 200 A** and argon flow rate **0.5 - 3 g/s**. We used welding machine current source.

Arc current was recorded with the sampling frequency **40 kHz** for approximately **6 seconds** in each experiment. For spectral analysis of signals we use *pwelch* method (Fourier analysis) implemented in MATLAB. Wavelet analysis is done using complex *Morlet* wavelet *cmor1-1*. Finally, we use the method of *time–embeddings* for reconstructing phase portraits of the measured process dynamics and *estimate correlation dimension* of these phase portraits.

HIGHER CURRENT LEADS TO STABILIZATION

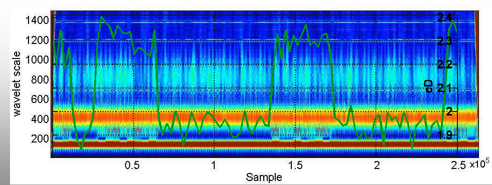
For the same argon flow rate **higher mean current** leads to **more stable dynamics**. This can be seen both as **lower** estimated **cD** and **suppression of 166.6 Hz** oscillation (wavelet scale 240).
Effect of the gas flow rate itself is not so clear. **Higher gas flow rate** usually leads to **less sable dynamics**, which is quite expectable. But we also documented examples of **exceptions** where there is less stable dynamics (**high cD**, **significant 166.6 Hz** oscillation) **even with lower gas flow rate**.

Record	Gas flow rate [g/s]	Mean current [A]	Maximum cD	Normalized PSD at 166.6Hz [log10]
1	0.5	109.3	2.34	- 4.715
2	0.5	205.7	1.74	- 7.221
3	1.2	161.8	2.42	- 4.658
4	1.2	162.0	1.99	- 7.130
5	2.0	152.1	2.38	- 4.253
6	2.0	152.1	1.99	- 7.208
7	2.5	147.3	2.04	- 7.252
8	2.5	147.5	2.03	- 6.790
9	3	143.8	2.39	- 4.343
10	3	143.7	2.40	- 4.413

Comparison of maximum of estimated cD with logarithm of normalized PSD at 166.6 Hz for different records.

WAVELET ANALYSIS DETECTS INTERVALS

While there is not any simple rule, we can see in the above table that in general **lower max. estimated cD** is accompanied by **lower amplitude** of PSD **at 166.6 Hz**. However, this analysis of overall spectra **does not provide** insight into the **specific time intervals** where dynamic **changes occur**.
Wavelet analysis provides us with this information. Naturally, we can find information about **the whole unstable intervals** at the **scale 240 points** (~**166.6 Hz**) . However, it seems that the **transitions in cD** exhibits themselves at **even larger wavelet scales**.



Evolution of estimated cD (green line) and concurrent wavelet analysis at multiple scales (gas flow rate 3 g/s).

CONCLUSION

Fourier and wavelet analysis confirms **difference** between records with **lower cD** and records containing intervals of **higher cD**. Former records contain oscillations at some dominant electric frequencies.
Latter records, in addition to that, contain significant additive oscillations at frequencies **+/- 16.6 Hz**, such as frequency **166.6 Hz** (~scale 240 points). It is quite possible, that 16.6 Hz is in fact 1/18 subharmonic of the dominant *300 Hz* frequency. This would confirm chaotic nature of the dynamics in these intervals, because amplification of subharmonics is one of the routes to deterministic chaos.
Fourier analysis provides **fast** way to **identify** the signal with some chaotic parts. **Wavelets** can detect **intervals** of chaotic dynamics and **transitions**. And **cD** estimation provides **compact** way to **quantify** the **stability** of the dynamics. All the methods complement each other nicely and provide an interesting tool for investigations of turbulence and transition to turbulence in various experimental conditions.