A note on energy forms on fractal domains
Claire David

To cite this version:
Claire David. A note on energy forms on fractal domains. 2017. hal-01508884

HAL Id: hal-01508884
https://hal.sorbonne-universite.fr/hal-01508884
Preprint submitted on 14 Apr 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
A note on energy forms on fractal domains

Claire David

April 14, 2017

Sorbonne Universités, UPMC Univ Paris 06
CNRS, UMR 7598, Laboratoire Jacques-Louis Lions, 4, place Jussieu 75005, Paris, France

1 Introduction

In [1], [2], J. Kigami has laid the foundations of what is now known as analysis on fractals, by allowing
the construction of an operator of the same nature of the Laplacian, defined locally, on graphs having
a fractal character. The Sierpiński gasket stands out of the best known example. It has, since then,
been taken up, developed and popularized by R. S. Strichartz [4], [20].

The Laplacian is obtained through a weak formulation, obtained by means of Dirichlet forms, built
by induction on a sequence of graphs that converges towards the considered domain. It is these Dirich-
let forms that enable one to obtain energy forms on this domain.

Yet, things are not that simple. If, for domains like the Sierpiński gasket, the Laplacian is obtained
in a quite natural way, one must bear in mind that Dirichlet forms solely depend on the topology of the
domain, and not of its geometry. Which means that, if one aims at building a Laplacian on a fractal
domain, the topology of which is the same as, for instance, a line segment, one has to find a way of
taking account a very specific geometry. We came across that problem in our work on the graph of
the Weierstrass function [6]. The solution was thus to consider energy forms more sophisticated than
classical ones, by means of normalization constants that could, not only bear the topology, but, also,
the very specific geometry of, from now on, we will call \( \mathcal{W} \)-curves.

It is interesting to note that such problems do not seem to arise so much in the existing literature.
In a very general way, one may refer to [8], where the authors build an energy form on non-self similar
closed fractal curves, by integrating the Lagrangian on this curve.

We presently aim at investigating the links between energy forms and geometry. We have chosen to
consider fractal curves, specifically, the Sierpiński arrowhead curve, the limit of which is the Sierpiński
gasket. Does one obtain the same Laplacian as for the triangle? The question appears as worth to be
investigated.
2 Framework of the study

We place ourselves, in the following, in the Euclidean plane of dimension 2, referred to a direct orthonormal frame. The usual Cartesian coordinates are \((x, y)\).

**Notation.** Given a point \(X \in \mathbb{R}^2\), we will denote by:

i. \(Sim_{X, \frac{1}{2}, \frac{\pi}{3}}\) the similarity of ratio \(\frac{1}{2}\), the center of which is \(X\), and the angle, \(\frac{\pi}{3}\);

ii. \(Sim_{X, \frac{1}{2}, \frac{\pi}{3}}\) the similarity of ratio \(\frac{1}{2}\), the center of which is \(X\), and the angle, \(-\frac{\pi}{3}\).

**Definition 2.1.** Let us consider the following points of \(\mathbb{R}^2\):

\[ A = (0, 0) \quad D = (1, 0) \quad B = Sim_{X, \frac{1}{2}, \frac{\pi}{3}}(D) \quad C = Sim_{X, \frac{1}{2}, \frac{\pi}{3}}(A) \]

We will denote by \(V_1\) the ordered set, of the points:

\[ \{A, B, C, D\} \]

The set of points \(V_1\), where \(A\) is linked to \(B\), \(B\) is linked to \(C\), and where \(C\) is linked to \(D\), constitutes an oriented graph, that we will denote by \(SG^C_1\). \(V_1\) is called the set of vertices of the graph \(SG^C_1\).

Let us build by induction the sequence of points:

\[ (V_m)_{m \in \mathbb{N}^*} = (X_j^m)_{1 \leq j \leq \mathcal{N}^S_m, m \in \mathbb{N}^*}, \quad \mathcal{N}^S_m \in \mathbb{N}^* \]

such that:

\[ X_1^1 = A \quad X_2^1 = B \quad X_3^1 = A \quad X_4^1 = D \]

and for any integers \(m \geq 2, 0 \leq j \leq \mathcal{N}^S_m, k \in \mathbb{N}, \ell \in \mathbb{N}:

\[ X_{j+k}^m = X_j^{m-1} \quad \text{if} \quad k \equiv 0 [3] \]

\[ X_{j+k+\ell}^m = Sim_{X_j^{m-1}, \frac{1}{2}, \frac{(\ell+1)m+\ell}{3}} (X_{j+1}^{m-1}) \quad \text{if} \quad k \equiv 1 [3] \quad \text{and} \quad \ell \in 2\mathbb{N} \]

\[ X_{j+k}^m = Sim_{X_j^{m-1}, \frac{1}{2}, \frac{(\ell+1)m+\ell}{3}} (X_j^{m-1}) \quad \text{if} \quad k \equiv 2 [3] \quad \text{and} \quad \ell \in \mathbb{N} \setminus 2\mathbb{N} \]

The set of points \(V_m\), where two consecutive points are linked, is an oriented graph, which we will denote by \(SG^C_m\). \(V_m\) is called the set of vertices of the graph \(SG^C_m\).

**Property 2.1.** For any strictly positive integer \(m\):

\[ V_m \subset V_{m+1} \]
Property 2.2. If one denotes by $(SG_m)_{m \in \mathbb{N}}$ the sequence of graphs that approximate the Sierpiński gasket $SG$, then, for any strictly positive integer $m$:

$$SG_m^C \subseteq SG_m$$

Definition 2.2. Sierpiński arrowhead curve
We will denote by $SG^C$ the limit:

$$SG^C = \lim_{m \to +\infty} SG_m^C$$

which will be called the Sierpiński arrowhead curve.

Property 2.3. Let us denote by $SG$ the Sierpiński Gasket. Then:

$$\lim_{m \to +\infty} SG_m^C = SG^C = SG$$

Remark 2.1. The sequence of graphs $(SG_m)_{m \in \mathbb{N}}$ can also be seen as a Lindenmayer system ("L-system"), i.e. a set $(V, \omega, P)$, where $V$ denotes an alphabet (or, equivalently, the set of constant elements and rules, and variables), $\omega$, the initial state (also called "axiom"), and $P$, the production rules, which are to be applied, iteratively, to the initial state.

In the case of the Sierpiński arrowhead curve, if one denotes by:

i. $F$ the rule: "Draw forward, on one unit length" ;

ii. $+$ the rule: "Turn left, with an angle of $\frac{\pi}{3}$" ;

iii. $-$ the rule: "Turn right, with an angle of $\frac{\pi}{3}$" ;

then:

i. the variables can be denoted by $X$ and $Y$ ;

ii. the constants are $F$, $+$, $-$ ;

iii. the initial state is $XF$ ;

iv. the production rules are:

$$X \to YF + XF + Y , \quad Y \to XF - YF - X$$
**Notation.** Given a point $X \in \mathbb{R}^2$, we will denote by $\mathcal{H}_{X,\frac{1}{2}}$ the homothecy of ratio $\frac{1}{2}$, the center of which is $X$.

**Property 2.4. Self-similarity properties of the Sierpiński arrowhead curve**

Let us denote by $E$ the point of $\mathbb{R}^2$ such that $A$, $D$ and $E$ are the consecutive vertices of a direct equilateral triangle. One may note that $A$, $D$ and $E$ are, also, the frontier vertices of the Sierpiński gasket $\mathcal{SG}$.

The Sierpiński arrowhead curve is self similar with the three homothecies:
Proof. The result comes from the self-similarity of the Sierpiński Gasket with respect to those homotecies:

\[
SG = \bigcup_{i=1}^{3} \mathcal{H}_i(SG)
\]

\[
\mathcal{H}_1 = \mathcal{H}_{A,\frac{1}{2}}, \quad \mathcal{H}_2 = \mathcal{H}_{D,\frac{1}{2}}, \quad \mathcal{H}_3 = \mathcal{H}_{E,\frac{1}{2}}
\]
Property 2.5. The sequence \((N^S_m)_{m \in \mathbb{N}}\) is an arithmetico-geometric one, with \(N^S_1 = 4\) as first term:

\[
\forall m \in \mathbb{N} : \quad N^S_{m+1} = 4 \left( N^S_m - 1 \right) - (N^S_m - 1) = 3N^S_m - 2
\]

This leads to:

\[
\forall m \in \mathbb{N}^* : \quad N^S_{m+1} = 3^m \left( N^S_1 - 1 \right) + 1 = 3^{m+1} + 1
\]

Definition 2.3. Consecutive vertices on the graph \(SG^C\)

Two points \(X\) and \(Y\) of \(SG^C\) will be called **consecutive vertices** of the graph \(SG^C\) if there exists a natural integer \(m\), and an integer \(j\) of \(\{1, \ldots, N^S_m - 1\}\), such that:

\[
X = X^m_j \quad \text{and} \quad Y = X^m_{j+1}
\]

or:

\[
Y = X^m_j \quad \text{and} \quad X = X^m_{j+1}
\]

Definition 2.4. For any positive integer \(m\), the \(N^S_m\) consecutive vertices of the graph \(SG^C_m\) are, also, the vertices of \(3^{m-1}\) trapezes \(T_{m,j}, 1 \leq j \leq 3^{m-1}\). For any integer \(j\) such that \(1 \leq j \leq 3^{m-1}\), one obtains each trapeze by linking the point number \(j\) to the point number \(j + 1\) if \(j = i \mod 4, 0 \leq i \leq 2\), and the point number \(j\) to the point number \(j - 3\) if \(j = -1 \mod 4\). These trapezes generate a Borel set of \(\mathbb{R}^2\).
In the sequel, we will denote by $T_1$ the initial trapeze, the vertices of which are, respectively:

\[ A, \ B, \ C, \ D \]

Figure 6: The trapezes $T_{2,1}$, $T_{2,2}$ and $T_{2,3}$.

**Definition 2.5. Trapezoidal domain delimited by the graph $SG^C_m$, $m \in \mathbb{N}$**

For any natural integer $m$, well call **trapezoidal domain delimited by the graph $SG^C_m$**, and denote by $D(SG^C_m)$, the reunion of the $3^{m-1}$ trapezes $T_{m,j}$, $1 \leq j \leq 3^{m-1}$.

**Property 2.6.** Taking into account that the Lebesgue measure of the first trapeze $T_1$ is given by:

\[ A_1 = A(T_1) = \frac{\sqrt{3}}{4} \]

one obtains, for any natural integer $m > 1$, the Lebesgue measure of a trapeze $T_{m,j}$, $1 \leq j \leq 3^{m-1}$ by noticing that each trapeze is, also, the reunion of three equilateral triangles.

Thus, for any natural integer $m \geq 2$, the Lebesgue measure of a trapeze $T_{m,j}$, $1 \leq j \leq 3^{m-1}$ is given by:

\[ A_m = A(T_{m,j}) = \frac{3A_1}{4^m} \]

**Definition 2.6. Trapezoidal domain delimited by the graph $SG^C$**

We will call **trapezoidal domain delimited by the graph $SG^C$**, and denote by $D(SG^C)$, the limit:

\[ D(SG^C) = \lim_{m \to +\infty} D(SG^C_m) \]
Notation. In the sequel, we will denote by $d_{\mathbb{R}^2}$ the Euclidean distance on $\mathbb{R}^2$.

Definition 2.7. Edge relation, on the graph $SG^C$

Given a natural integer $m$, two points $X$ and $Y$ of $SG^C_m$ will be called adjacent if and only if $X$ and $Y$ are two consecutive vertices of $SG^C_m$. We will write:

\[ X \sim_m Y \]

Given two points $X$ and $Y$ of the graph $SG^C$, we will say that $X$ and $Y$ are adjacent if and only if there exists a natural integer $m$ such that:

\[ X \sim_m Y \]

Property 2.7. Euclidean distance of two adjacent vertices of $SG^C_m$, $m \in \mathbb{N}$

Given a natural integer $m$, and two points $X$ and $Y$ of $SG^C_m$ such that $X \sim_m Y$:

\[ d_{\mathbb{R}^2}(X,Y) = \frac{1}{2^m} \]

Property 2.8. The set of vertices $(V_m)_{m \in \mathbb{N}}$ is dense in $SG^C$.

Definition 2.8. Measure, on the domain delimited by the graph $SG^C$

We will call domain delimited by the graph $SG^C$, and denote by $D(SG^C)$, the limit:

\[ D(SG^C) = \lim_{n \to +\infty} D(SG^C_n) \]

which has to be understood in the following way: given a continuous function $u$ on the graph $SG^C$, and a measure with full support $\mu$ on $\mathbb{R}^2$, then:

\[
\int_{D(SG^C)} u \, d\mu = \lim_{m \to +\infty} \sum_{j=1}^{2^{m-1}} \sum_{X \text{ vertex of } T_{m,j}} u(X) \, \mu(T_{m,j})
\]

We will say that $\mu$ is a measure, on the domain delimited by the graph $SG^C$.

Definition 2.9. Dirichlet form (we refer to the paper [14], or the book [23])

Given a measured space $(E, \mu)$, a Dirichlet form on $E$ is a bilinear symmetric form, that we will denote by $\mathcal{E}$, defined on a vectorial subspace $D$ dense in $L^2(E, \mu)$, such that:

1. For any real-valued function $u$ defined on $D$, $\mathcal{E}(u, u) \geq 0$. 

8
2. $D$, equipped with the inner product which, to any pair $(u, v)$ of $D \times D$, associates:

$$(u, v)_E = (u, v)_{L^2(E, \mu)} + \mathcal{E}(u, v)$$

is a Hilbert space.

3. For any real-valued function $u$ defined on $D$, if:

$$u_* = \min(\max(u, 0), 1) \in D$$

then: $\mathcal{E}(u_*, u_*) \leq \mathcal{E}(u, u)$ (Markov property, or lack of memory property).

**Definition 2.10. Dirichlet form, on a finite set ([2])**

Let $V$ denote a finite set $V$, equipped with the usual inner product which, to any pair $(u, v)$ of functions defined on $V$, associates:

$$(u, v) = \sum_{p \in V} u(p) v(p)$$

A *Dirichlet form* on $V$ is a symmetric bilinear form $\mathcal{E}$, such that:

1. For any real valued function $u$ defined on $V$: $\mathcal{E}(u, u) \geq 0$.
2. $\mathcal{E}(u, u) = 0$ if and only if $u$ is constant on $V$.
3. For any real-valued function $u$ defined on $V$, if:

$$u_* = \min(\max(u, 0), 1)$$

i.e. :

$$\forall p \in V : \quad u_*(p) = \begin{cases} 
1 & \text{if } u(p) \geq 1 \\
 u(p) & \text{if } 0 < u(p) < 1 \\
 0 & \text{if } u(p) \leq 0 
\end{cases}$$

then: $\mathcal{E}(u_*, u_*) \leq \mathcal{E}(u, u)$ (Markov property).

**Notation.** Let us denote by:

$$D_{SG^c} = D_{SG} = \frac{\ln 3}{\ln 2}$$

the box-dimension (equal to the Hausdorff dimension), of the Sierpiński arrow curve $SG^c$.

For the sake of simplicity, we will from now on denote it by $D_{SG}$.

Let us now consider the problem of energy forms on our curve. The following points have to be taken into account:
i. As mentioned in the preamble of this work, Dirichlet forms solely depend on the topology of the sequence of graphs that approximate our curve.

ii. Our curve is, indeed, self-similar, yet, it cannot be obtained by means of an iterated function system, as it is the case with the Sierpiński gasket, or the \( \mathcal{W} \)-curve we studied in [6].

Such a problem was studied by U. Mosco [7], who specifically considered the case of what he called "the Sierpiński curve", or "Sierpiński string". Yet, he did not dealt with the curve itself, but with the Sierpiński gasket: "2D branches (...) meet together". Contrary to the arrow curve, the Sierpiński gasket exhibits self-similarity properties which turn it into a post-critically finite fractal (pcf fractal).

Yet, one can find interesting ideas in the work of U. Mosco. For instance, he suggests to generalize Riemannian models to fractals and relate the fractal analogous of gradient forms, i.e. the Dirichlet forms, to a metric that could reflect the fractal properties of the considered structure. The link is to be made by means of specific energy forms.

There are two major features that enable one to characterize fractal structures:

i. Their topology, i.e. their ramification.

ii. Their geometry.

The topology can be taken into account by means of classical energy forms (we refer to [1], [2], [4], [20]).

As for the geometry, again, things are not that simple to handle. U. Mosco introduces a strictly positive parameter, \( \delta \), which is supposed to reflect the way ramification - or the iterative process that gives birth to the sequence of graphs that approximate the structure - affects the initial geometry of the structure. For instance, if \( m \) is a natural integer, \( X \) and \( Y \) two points of the initial graph \( V_1 \), and \( M \) a word of length \( m \), the Euclidean distance \( d_{\mathbb{R}^2}(X, Y) \) between \( X \) and \( Y \) is changed into the effective distance:

\[
(d_{\mathbb{R}^2}(X, Y))^\delta
\]

This parameter \( \delta \) appears to be the one that can be obtained when building the effective resistance metric of a fractal structure (see [20]), which is obtained by means of energy forms. To avoid turning into circles, this means:

i. either working, in a first time, with a value \( \delta_0 \) equal to one, and, then, adjusting it when building the effective resistance metric;

ii. using existing results, as done in [8].

In the case of the arrow curve, at a step \( m \in \mathbb{N}^* \) of the iteration process, the distance between two adjacent points of \( SG_m \) is the same as the one between two adjacent points of the graph \( SG_m \), and take:

\[
\delta = \frac{\ln 5}{\ln 4}
\]
Definition 2.11. Energy, on the graph $\mathcal{S}_m^C$, $m \in \mathbb{N}$, of a pair of functions

Let $m$ be a natural integer, and $u$ and $v$ two real valued functions, defined on the set

$$V_m = \{X_1^m, \ldots, X_{N^S_m}^m\}$$

of the $N^S_m$ vertices of $\mathcal{S}_m^C$.

We introduce the energy, on the graph $\mathcal{S}_m^C$, of the pair of functions $(u, v)$, as:

$$E_{\mathcal{S}_m^C}(u, v) = \sum_{i=1}^{N^S_m-1} \left( \frac{u(X_i^m) - u(X_{i+1}^m)}{d_{\mathbb{R}^2}(X, Y)} \right) \left( \frac{v(X_i^m) - v(X_{i+1}^m)}{d_{\mathbb{R}^2}(X, Y)} \right)$$

For the sake of simplicity, we will write it under the form:

$$E_{\mathcal{S}_m^C}(u, v) = \sum_{X \sim Y} 4^m \delta (u(X) - u(Y)) (v(X) - v(Y))$$

Property 2.9. Given a natural integer $m$, and a real-valued function $u$, defined on the set of vertices of $\mathcal{S}_m^C$, the map, which, to any pair of real-valued, continuous functions $(u, v)$ defined on the set $V_m$ of the $N_m$ vertices of $\mathcal{S}_m^C$, associates:

$$E_{\mathcal{S}_m^C}(u, v) = \sum_{X \sim Y} 4^m \delta (u(X) - u(Y)) (v(X) - v(Y))$$

is a Dirichlet form on $\mathcal{S}_m^C$.

Moreover:

$$E_{\mathcal{S}_m^C}(u, u) = 0 \iff u \text{ is constant}$$

Proposition 2.10. Harmonic extension of a function, on the graph of Sierpiński arrow curve - Ramification constant

For any integer $m > 1$, if $u$ is a real-valued function defined on $V_{m-1}$, its harmonic extension, denoted by $\tilde{u}$, is obtained as the extension of $u$ to $V_m$ which minimizes the energy:

$$E_{\mathcal{S}_{m-1}^C}(\tilde{u}, \tilde{u}) = \sum_{X \sim Y} 4^m \delta (\tilde{u}(X) - \tilde{u}(Y))^2$$

The link between $E_{\mathcal{S}_m^C}$ and $E_{\mathcal{S}_{m-1}^C}$ is obtained through the introduction of two strictly positive constants $r_m$ and $r_{m+1}$ such that:

$$r_m \sum_{X \sim Y} 4^m \delta (\tilde{u}(X) - \tilde{u}(Y))^2 = r_{m-1} 4^m \sum_{X \sim Y} (u(X) - u(Y))^2$$

In particular:
\[
\sum_{X_i Y_j} 2 (\tilde{u}(X) - \tilde{u}(Y))^2 = r_1 \sum_{X_i Y_j} (u(X) - u(Y))^2
\]

For the sake of simplicity, we will fix the value of the initial constant: \( r_1 = 1 \). One has then:

\[
E_{SC_m}(\tilde{u}, \tilde{u}) = \frac{1}{r_1} E_{SC_1}(\tilde{u}, \tilde{u})
\]

Let us set:

\[
r = \frac{1}{r_1}
\]

and:

\[
E_m(u) = r_m \sum_{X_i Y_j} 4^{m \delta} (\tilde{u}(X) - \tilde{u}(Y))^2
\]

Since the determination of the harmonic extension of a function appears to be a local problem, on the graph \( W_{m-1} \), which is linked to the graph \( SC_m \) by a similar process as the one that links \( SC_2 \) to \( SC_1 \), one deduces, for any integer \( m > 2 \):

\[
E_{SC_m}(\tilde{u}, \tilde{u}) = \frac{1}{r_1} E_{SC_{m-1}}(\tilde{u}, \tilde{u})
\]

By induction, one gets:

\[
r_m = r_1^m = r^{-m} = 3^{-m}
\]

If \( v \) is a real-valued function, defined on \( V_{m-1} \), of harmonic extension \( \tilde{v} \), we will write:

\[
E_m(u, v) = r^{-m} \sum_{X_i Y_j} 4^{m \delta} (\tilde{u}(X) - \tilde{u}(Y))(\tilde{v}(X) - \tilde{v}(Y))
\]

The constant \( r^{-1} \), which can be interpreted as a topological one, will be called \textbf{ramification constant}.

For further precision on the construction and existence of harmonic extensions, we refer to [13].

\textbf{Remark 2.2. Determination of the ramification constant} \( r \)

Let us denote by \( u \) a real-valued, continuous function defined on \( V_1 \), and by \( \tilde{u} \) its harmonic extension to \( V_2 \).

Let us denote by \( a, b, c \) and \( d \) the values of \( u \) on the four consecutive vertices of \( V_1 \) (see the following figure):

\[
u(A) = a \quad , \quad u(B) = b \quad , \quad u(C) = c \quad , \quad u(D) = d
\]

and by:

\[\begin{align*}
i. & \quad e \text{ and } f \text{ the values of } \tilde{u} \text{ on the two consecutive vertices } E \text{ and } F \text{ that are between } A \text{ and } B: \\
& \quad u(E) = e \quad , \quad u(F) = f
\end{align*}\]

\[\begin{align*}
ii. & \quad g \text{ and } h \text{ the values of } \tilde{u} \text{ on the two consecutive vertices } G \text{ and } H \text{ that are between } B \text{ and } C: \\
& \quad u(G) = g \quad , \quad u(H) = h
\end{align*}\]
Figure 7: Determination of the ramification constant between graphs of level 1 and 2.

iii. $i$ and $j$ the values of $\tilde{u}$ on the two consecutive vertices $I$ and $J$ that are between $C$ and $D$:

$$u(I) = i, \quad u(J) = j$$

One has:

$$E_{SG_1}(\tilde{u}, \tilde{u}) = (a - b^2 + (b - c)^2 + (c - d)^2)$$

$$E_{SG_2}(\tilde{u}, \tilde{u}) = (a - e)^2 + (e - f)^2 + (b - f)^2 + (g - b)^2 + (h - g)^2 + (c - h)^2 + (i - c)^2 + (j - i)^2 + (d - j)^2$$

Since the harmonic extension $\tilde{u}$ minimizes $E_{SG_2}$, the values of $e, f, g, h, i, j$ are to be found among the critical points $e, f, g, h, i, j$ such that:

$$\frac{\partial E_{SG_2}(\tilde{u}, \tilde{u})}{\partial e} = 0, \quad \frac{\partial E_{SG_2}(\tilde{u}, \tilde{u})}{\partial f} = 0, \quad \frac{\partial E_{SG_2}(\tilde{u}, \tilde{u})}{\partial g} = 0, \quad \frac{\partial E_{SG_2}(\tilde{u}, \tilde{u})}{\partial h} = 0, \quad \frac{\partial E_{SG_2}(\tilde{u}, \tilde{u})}{\partial i} = 0, \quad \frac{\partial E_{SG_2}(\tilde{u}, \tilde{u})}{\partial j} = 0$$

This leads to:

$$e = \frac{2a + b}{3}, \quad f = \frac{2(a + 2b)}{3}, \quad g = \frac{2b + c}{3}, \quad h = \frac{2(b + 2c)}{3}, \quad i = \frac{2c + d}{3}, \quad j = \frac{2(c + 2d)}{3}$$

and:

$$E_{SG_2}(\tilde{u}, \tilde{u}) = \frac{1}{3} E_{SG_2}(\tilde{u}, \tilde{u})$$

Thus:

$$r^{-1} = \frac{1}{3}$$

One may note that the ramification constant is exactly equal to one plus the number of points that arise in $V_{m+1}$, for any value of the strictly positive integer $m$, between two consecutive vertices of $V_m$.

We thus fall back on the results we previously obtained in [18], [6] for the graph of the Weierstrass function.

**Definition 2.12. Energy scaling factor**

By definition, the **energy scaling factor** is the strictly positive constant $\rho$ such that, for any integer $m > 1$, and any real-valued function $u$ defined on $V_m$:

$$E_{SG_m}(u, u) = \rho E_{SG_m}(u|_{V_{m-1}}, u|_{V_{m-1}})$$
Proposition 2.11. The energy scaling factor $\rho$ is linked to the topology and the geometry of the fractal curve by means of the relation:

$$\rho = \frac{4^\delta}{3}$$

Definition 2.13. Dirichlet form, for a pair of continuous functions defined on the graph $SG^C$

We define the Dirichlet form $\mathcal{E}$ which, to any pair of real-valued, continuous functions $(u, v)$ defined on the Sierpiński arrow curve $SG^C$, associates, subject to its existence:

$$\mathcal{E}(u, v) = \lim_{m \to +\infty} \mathcal{E}_m \left( u|_{V_m}, v|_{V_m} \right) = \lim_{m \to +\infty} \sum_{X \sim Y} r^{-m} 4^m \delta \left( u|_{V_m}(X) - u|_{V_m}(Y) \right) \left( v|_{V_m}(X) - v|_{V_m}(Y) \right)$$

Definition 2.14. Normalized energy, for a continuous function $u$, defined on the Sierpiński arrow curve

Taking into account that the sequence $\left( \mathcal{E}_m \left( u|_{V_m} \right) \right)_{m \in \mathbb{N}}$ is defined on

$$V_\star = \bigcup_{i \in \mathbb{N}} V_i$$

one defines the normalized energy, for a continuous function $u$, defined on the curve $SG^C$, by:

$$\mathcal{E}(u) = \lim_{m \to +\infty} \mathcal{E}_m \left( u|_{V_m} \right)$$

Notation. We will denote by $\text{dom} \mathcal{E}$ the subspace of continuous functions defined on $SG^C$, such that:

$$\mathcal{E}(u) < +\infty$$

Notation. We will denote by $\text{dom}_1 \mathcal{E}$ the subspace of continuous functions defined on $SG^C$, which take the value on $V_1$, such that:

$$\mathcal{E}(u) < +\infty$$
3 Laplacian of a continuous function, on the Sierpiński arrowhead curve

Definition 3.1. Self-similar measure, on the graph of the Sierpiński arrow curve

A measure $\mu$ on $\mathbb{R}^2$ will be said to be self-similar for the domain delimited by the Sierpiński arrow curve, if there exists a family of strictly positive pounds $(\mu_1, \mu_2, \mu_3)$ such that:

$$\mu = \sum_{i=1}^{3} \mu_i \circ \mathcal{H}_i^{-1}, \quad \sum_{i=1}^{3} \mu_i = 1$$

For further precisions on self-similar measures, we refer to the works of J. E. Hutchinson (see [?]).

Property 3.1. Building of a self-similar measure, for the domain delimited by the Sierpiński arrow curve

The Dirichlet forms mentioned in the above require a positive Radon measure with full support. The choice of a self-similar measure, which is, most of the time, built with regards to a reference set, of measure 1, appears, first, as very natural. R. S. Strichartz [3], [4], showed that one can simply consider auto-replicant measures $\tilde{\mu}$, i.e. measures $\tilde{\mu}$ such that:

$$\tilde{\mu} = \sum_{i=1}^{3} \tilde{\mu}_i \circ \mathcal{H}_i^{-1} \quad (\ast)$$

where $(\tilde{\mu}_1, \tilde{\mu}_2, \tilde{\mu}_3)$ denotes a family of strictly positive pounds.

This latter approach appears as the best suited in our study, since, in the case of the graph $\mathcal{S} \mathcal{G}^C$, the initial set consists of the trapeze $T_0$, the measure of which, equal to its surface, is not necessarily equal to 1.

Let us assume that there exists a measure $\tilde{\mu}$ satisfying $(\ast)$. Relation $(\ast)$ yields, for any set of trapezes $T_{m,j}$, $m \in \mathbb{N}$, $1 \leq j \leq 3^{m-1}$:

$$\tilde{\mu} \left( \bigcup_{1 \leq j \leq 3^{m-1}} T_{m,j} \right) = \sum_{i=1}^{3} \tilde{\mu}_i \tilde{\mu} \left( \mathcal{H}_i^{-1} \left( \bigcup_{1 \leq j \leq 3^{m-1}} T_{m,j} \right) \right)$$

and, in particular:

$$\tilde{\mu} \left( \mathcal{H}_1(T_1) \cup \mathcal{H}_2(T_1) \cup \mathcal{H}_3(T_1) \right) = \sum_{i=1}^{3} \tilde{\mu}_i \tilde{\mu} \left( T_1 \right)$$

i.e.: 

$$\sum_{i=1}^{3} \tilde{\mu} \left( \mathcal{H}_i(T_1) \right) = \sum_{i=1}^{3} \tilde{\mu}_i \tilde{\mu} \left( T_1 \right)$$

The convenient choice, for any $i$ of $\{1,2,3\}$, is:

$$\tilde{\mu}_i = \frac{\tilde{\mu} \left( \mathcal{H}_i(T_1) \right)}{\tilde{\mu} \left( T_1 \right)} = \frac{3}{4}$$

One can, from the measure $\tilde{\mu}$, build the self-similar measure $\mu$, such that:
\[ \mu = \sum_{i=1}^{3} \mu_i \circ \mathcal{H}_i^{-1} \]

where \((\mu_i)_{1 \leq i \leq 3}\) is a family of strictly positive pounds, the sum of which is equal to 1.

One has simply to set, for any \(i\) of \(\{1, 2, 3\}\):

\[ \mu_i = \frac{4 \tilde{\mu}_i}{9} \]

The measure \(\mu\) is self-similar, for the domain delimited by the Sierpiński arrowhead curve.

**Definition 3.2. Laplacian of order** \(m \in \mathbb{N}^*\)

For any strictly positive integer \(m\), and any real-valued function \(u\), defined on the set \(V_m\) of the vertices of the graph \(SG_m^C\), we introduce the Laplacian of order \(m\), \(\Delta_m(u)\), by:

\[ \Delta_m u(X) = \sum_{Y \in V_m, \mathcal{Y} \sim X} (u(Y) - u(X)) \quad \forall X \in V_m \setminus V_0 \]

**Definition 3.3. Harmonic function of order** \(m \in \mathbb{N}^*\)

Let \(m\) be a strictly positive integer. A real-valued function \(u\), defined on the set \(V_m\) of the vertices of the graph \(SG_m^C\), will be said to be harmonic of order \(m\) if its Laplacian of order \(m\) is null:

\[ \Delta_m u(X) = 0 \quad \forall X \in V_m \setminus V_0 \]

**Definition 3.4. Piecewise harmonic function of order** \(m \in \mathbb{N}^*\)

Given a strictly positive integer \(m\), a real valued function \(u\), defined on the set of vertices of \(SG^C\), is said to be piecewise harmonic function of order \(m\) if, for any word \(M\) of length \(m\), \(u \circ T_M\) is harmonic of order \(m\).

**Definition 3.5. Existence domain of the Laplacian, for a continuous function on the graph** \(SG^C\) (see [14])

We will denote by \(\text{dom} \Delta\) the existence domain of the Laplacian, on the graph \(SG^C\), as the set of functions \(u\) of \(\text{dom} \mathcal{E}\) such that there exists a continuous function on \(SG^C\), denoted \(\Delta u\), that we will call Laplacian of \(u\), such that :

\[ \mathcal{E}(u, v) = -\int_{D(SG^C)} v \Delta u \, d\mu \quad \text{for any} \ v \in \text{dom}_1 \mathcal{E} \]

**Definition 3.6. Harmonic function**

A function \(u\) belonging to \(\text{dom} \Delta\) will be said to be harmonic if its Laplacian is equal to zero.
**Notation.** In the following, we will denote by $\mathcal{H}_0 \subseteq \text{dom} \Delta$ the space of harmonic functions, i.e. the space of functions $u \in \text{dom} \Delta$ such that:

$$\Delta u = 0$$

Given a natural integer $m$, we will denote by $\mathcal{S}(\mathcal{H}_0, V_m)$ the space, of dimension $N^m_b$, of spline functions "of level $m"$, $u$, defined on $\mathcal{S}\mathcal{G}^C$, continuous, such that, for any word $M$ of length $m$, $u \circ T_M$ is harmonic, i.e.:

$$\Delta_m (u \circ T_M) = 0$$

**Property 3.2.** For any natural integer $m$:

$$\mathcal{S}(\mathcal{H}_0, V_m) \subseteq \text{dom} \mathcal{E}$$

**Property 3.3.** Let $m$ be a strictly positive integer, $X \notin V_0$ a vertex of the graph $\mathcal{S}\mathcal{G}^C$, and $\psi^m_X \in \mathcal{S}(\mathcal{H}_0, V_m)$ a spline function such that:

$$\psi^m_X(Y) = \begin{cases} 
\delta_{XY} & \forall \ Y \in V_m \\
0 & \forall \ Y \notin V_m 
\end{cases}, \quad \text{where} \quad \delta_{XY} = \begin{cases} 
1 & \text{if} \ X = Y \\
0 & \text{else}
\end{cases}$$

Then, since $X \notin V_0$: $\psi^m_X \in \text{dom}_1 \mathcal{E}$.

For any function $u$ of $\text{dom} \mathcal{E}$, such that its Laplacian exists, definition (3.5) applied to $\psi^m_X$ leads to:

$$\mathcal{E}(u, \psi^m_X) = \eta^2_{2-DW} \mathcal{E}_m(u, \psi^m_X) = -r^{-m} \eta^2_{2-DW} \Delta_m u(X) = - \int_{\mathcal{D}(\mathcal{S}\mathcal{G}^C)} \psi^m_X \Delta u \, d\mu \approx -\Delta u(X) \int_{\mathcal{D}(\mathcal{S}\mathcal{G}^C)} \psi^m_X \, d\mu$$

since $\Delta u$ is continuous on $\mathcal{S}\mathcal{G}^C$, and the support of the spline function $\psi^m_X$ is close to $X$:

$$\int_{\mathcal{D}(\mathcal{S}\mathcal{G}^C)} \psi^m_X \Delta u \, d\mu \approx -\Delta u(X) \int_{\mathcal{D}(\mathcal{S}\mathcal{G}^C)} \psi^m_X \, d\mu$$

By passing through the limit when the integer $m$ tends towards infinity, one gets:

$$\lim_{m \to +\infty} \int_{\mathcal{D}(\mathcal{S}\mathcal{G}^C)} \psi^m_X \Delta_m u \, d\mu = \Delta u(X) \lim_{m \to +\infty} \int_{\mathcal{D}(\mathcal{S}\mathcal{G}^C)} \psi^m_X \, d\mu$$

i.e.:

$$\Delta u(X) = \lim_{m \to +\infty} r^{-m} A^m \delta \left( \int_{\mathcal{D}(\mathcal{S}\mathcal{G}^C)} \psi^m_X \, d\mu \right)^{-1} \Delta_m u(X)$$
4 Explicit determination of the Laplacian of a function $u$ of $\text{dom} \Delta$

The explicit determination of the Laplacian of a function $u$ of $\text{dom} \Delta$ requires to know:

$$\int_{D(SG^c)} \psi_X^m \, d\mu$$

As it is explained in [20], one has just to reason by analogy with the dimension 1, more particularly, the unit interval $I = [0, 1]$, of extremities $X_0 = (0, 0)$, and $X_1 = (1, 0)$. The functions $\psi_{X_1}$ and $\psi_{X_2}$ such that, for any $Y$ of $\mathbb{R}^2$:

$$\psi_{X_1}(Y) = \delta_{X_1 Y} \quad , \quad \psi_{X_2}(Y) = \delta_{X_2 Y}$$

are, in the most simple way, tent functions. For the standard measure, one gets values that do not depend on $X_1$, or $X_2$ (one could, also, choose to fix $X_1$ and $X_2$ in the interior of $I$) :

$$\int_I \psi_{X_1} \, d\mu = \int_I \psi_{X_2} \, d\mu = \frac{1}{2}$$

(which corresponds to the surfaces of the two tent triangles.)

![Figure 8: The graphs of the spline functions $\psi_{X_1}$ and $\psi_{X_2}$.](image)

In our case, we have to build the pendant, we no longer reason on the unit interval, but on our trapezes.
Given a strictly positive integer $m$, and a vertex $X$ of the graph $SG^C_m$, two configurations can occur:

i. the vertex $X$ belongs to one and only one trapeze $T_{m,j}$, $1 \leq j \leq 3^{m-1}$.

In this case, if one considers the spline functions $\psi^n_Z$ which correspond to the 3 vertices of this trapeze distinct from $X$:

$$\sum_{Z \text{ vertex of } T_{m,j}} \int_{D(SG^C)} \psi^n_Z \, d\mu = \mu (T_{m,j})$$

i.e., by symmetry:

$$N_b \int_{D(SG^C)} \psi^n_X \, d\mu = \mu (T_{m,j})$$

Thus:

$$\int_{D(SG^C)} \psi^n_X \, d\mu = \frac{1}{4} \mu (T_{m,j})$$

![Figure 9: The graph of a spline function $\psi^n_X$, $m \in \mathbb{N}$.]

ii. the vertex $X$ is the intersection point of two trapezes $T_{m,j}$ and $T_{m,j+1}$, $1 \leq j \leq 3^{m-1}$.

On has then to take into account the contributions of both trapezes, which leads to:

$$\int_{D(SG^C)} \psi^n_X \, d\mu = \frac{1}{8} \left\{ \mu (T_{m,j}) + \mu (T_{m,j+1}) \right\}$$
Theorem 4.1. Let \( u \) be in \( \text{dom} \Delta \). Then, the sequence of functions \( \{f_m\}_{m \in \mathbb{N}} \), such that, for any strictly positive integer \( m \), and any \( X \) of \( V_\star \setminus V_1 \):

\[
f_m(X) = r^{-m} 4^m \delta \left( \int_{\mathcal{D}(SG^C)} \psi^m_X d\mu \right)^{-1} \Delta_m u(X)
\]

converges uniformly towards \( \Delta u \), and, reciprocally, if the sequence of functions \( \{f_m\}_{m \in \mathbb{N}} \), converges uniformly towards a continuous function on \( V_\star \setminus V_0 \), then:

\[
u \in \text{dom} \Delta
\]

Proof. Let \( u \) be in \( \text{dom} \Delta \). Then:

\[
r^{-m} 4^m \delta \left( \int_{\mathcal{D}(SG^C)} \psi^m_X d\mu \right)^{-1} \Delta_m u(X) = \frac{\int_{\mathcal{D}(SG^C)} \Delta u \psi^m_X d\mu}{\int_{\mathcal{D}(SG^C)} \psi^m_X d\mu}
\]

Since \( u \) belongs to \( \text{dom} \Delta \), its Laplacian \( \Delta u \) exists, and is continuous on the graph \( SG^C \). The uniform convergence of the sequence \( \{f_m\}_{m \in \mathbb{N}} \) follows.

Reciprocally, if the sequence of functions \( \{f_m\}_{m \in \mathbb{N}} \), converges uniformly towards a continuous function on \( V_\star \setminus V_1 \), the, for any natural integer \( m \), and any \( v \) belonging to \( \text{dom}_1 \mathcal{E} \):

\[
\mathcal{E}_m(u,v) = \sum_{(X,Y) \in V_m^2, X \sim Y} r^{-m} 4^m \delta \left( u_{|V_m}(X) - u_{|V_m}(Y) \right) \left( v_{|V_m}(X) - v_{|V_m}(Y) \right)
\]

\[
= \sum_{(X,Y) \in V_m^2, X \sim Y} r^{-m} 4^m \delta \left( u_{|V_m}(Y) - u_{|V_m}(X) \right) \left( v_{|V_m}(X) - v_{|V_m}(Y) \right)
\]

\[
= \sum_{X \in V_m \setminus V_1} v(X) \left( \int_{\mathcal{D}(SG^C)} \psi^m_X d\mu \right) r^{-m} 4^m \delta \left( \int_{\mathcal{D}(SG^C)} \psi^m_X d\mu \right)^{-1} \Delta_m u(X)
\]

Let us note that any \( X \) of \( V_m \setminus V_1 \) admits exactly two adjacent vertices which belong to \( V_m \setminus V_1 \), which accounts for the fact that the sum

\[
\sum_{X \in V_m \setminus V_1} r^{-m} 4^m \delta \sum_{Y \in V_m \setminus V_1, Y \sim X} v(X) \left( u_{|V_m}(Y) - u_{|V_m}(X) \right)
\]

has the same number of terms as:

\[
\sum_{(X,Y) \in (V_m \setminus V_1)^2, X \sim Y} r^{-m} 4^m \delta \left( u_{|V_m}(Y) - u_{|V_m}(X) \right) \left( v_{|V_m}(X) - v_{|V_m}(Y) \right)
\]

For any natural integer \( m \), we introduce the sequence of functions \( \{f_m\}_{m \in \mathbb{N}} \), such that, for any \( X \) of \( V_m \setminus V_1 \):
The sequence \((f_m)_{m \in \mathbb{N}}\) converges uniformly towards \(\Delta u\). Thus:

\[
\mathcal{E}_m(u, v) = -\int_{D(\mathcal{S}G^c)} \left\{ \sum_{X \in V_m \setminus V_i} v_{|V_m}(X) \Delta u_{|V_m}(X) \psi^m_X \right\} d\mu
\]

\[
\square
\]

### 4.1 Spectrum of the Laplacian

In the following, let \(u\) be in \(\text{dom} \Delta\). We will apply the **spectral decimation method** developed by R. S. Strichartz [20], in the spirit of the works of M. Fukushima et T. Shima [23]. In order to determine the eigenvalues of the Laplacian \(\Delta u\) built in the above, we concentrate first on the eigenvalues \((-\Lambda_m)_{m \in \mathbb{N}}\) of the sequence of graph Laplacians \((\Delta_m u)_{m \in \mathbb{N}}\) built on the discrete sequence of graphs \((\Gamma_{V_m})_{m \in \mathbb{N}}\). For any natural integer \(m\), the restrictions of the eigenfunctions of the continuous Laplacian \(\Delta u\) to the graph \(\Gamma_{V_m}\) are, also, eigenfunctions of the Laplacian \(\Delta_m\), which leads to recurrence relations between the eigenvalues of order \(m\) and \(m+1\).

We thus aim at determining the solutions of the eigenvalue equation:

\[
-\Delta u = \Lambda u \quad \text{on} \quad \mathcal{S}G^c
\]

as limits, when the integer \(m\) tends towards infinity, of the solutions of:

\[
-\Delta_m u = \Lambda_m u \quad \text{on} \quad V_m \setminus V_0
\]

Let \(m \geq 2\). We consider an eigenfunction \(u_{m-1}\) on \(V_{m-1} \setminus V_1\), for the eigenvalue \(\Lambda_{m-1}\). The aim is to extend \(u_{m-1}\) on \(V_m \setminus V_1\) in a function \(u_m\), which will itself be an eigenfunction of \(\Delta_m\), for the eigenvalue \(\Lambda_m\), and, thus, to obtain a recurrence relation between the eigenvalues \(\Lambda_m\) and \(\Lambda_{m-1}\). Given three consecutive vertices of \(\mathcal{S}G^c_{m-1}\), \(X_k, X_{k+1}, X_{k+2}\), where \(k\) denotes a generic natural integer, we will denote by \(Y_{k+1}, Y_{k+2}\) the points of \(V_m \setminus V_{m-1}\) such that: \(Y_{k+1}, Y_{k+2}\) are between \(X_k\) and \(X_{k+1}\), by \(Y_{k+4}, Y_{k+5}\), the points of \(V_m \setminus V_{m-1}\) such that: \(Y_{k+4}, Y_{k+5}\) are between \(X_{k+1}\) and \(X_{k+2}\), and by \(Y_{k+7}, Y_{k+8}\), the points of \(V_m \setminus V_{m-1}\) such that: \(Y_{k+7}, Y_{k+8}\) are between \(X_{k+2}\) and \(X_{k+3}\). For the sake of consistency, let us set:

\[
Y_k = X_k, \quad Y_{k+3} = X_{k+1}, \quad Y_{k+6} = X_{k+2}, \quad Y_{k+9} = X_{k+3}
\]

The eigenvalue equation in \(\Lambda_m\) leads to the following system:

\[
\begin{align*}
\begin{cases}
\{A_m - 2\} u_m(Y_{k+i+1}) = -u_m(Y_{k+i}) - u_m(Y_{k+i+2}) = -u_{m-1}(X_{k+i}) - u_m(Y_{k+i+2}) & , 0 \leq i \leq 2
\end{cases}
\end{align*}
\]

The sequence \((u_m(Y_{k+i}))_{0 \leq i \leq 9}\) satisfies a second order recurrence relation, the characteristic equation of which is:

\[
r^2 + \{A_m - 2\} r + 1 = 0
\]

The discriminant is:
The roots $r_{1,m}$ and $r_{2,m}$ of the characteristic equation are the scalar given by:

$$r_{1,m} = \frac{2 - \Lambda_m - \omega_m}{2}, \quad r_{2,m} = \frac{2 - \Lambda_m + \omega_m}{2}$$

One has then, for any natural integer $i$ of $\{0, \ldots, 9\}$:

$$u_m(Y_{k+i}) = \alpha_m r_{1,m}^i + \beta_m r_{2,m}^i$$

where $\alpha_m$ and $\beta_m$ denote scalar constants.

From this point, the compatibility conditions, imposed by spectral decimation, have to be satisfied:

$$\begin{align*}
  u_m(Y_k) &= u_{m-1}(X_k) \\
  u_m(Y_{k+3}) &= u_{m-1}(X_{k+1}) \\
  u_m(Y_{k+6}) &= u_{m-1}(X_{k+2}) \\
  u_m(Y_{k+9}) &= u_{m-1}(X_{k+3})
\end{align*}$$

i.e.:
\[
\begin{align*}
\alpha_m + \beta_m &= \alpha_{m-1} + \beta_{m-1} & C_m \\
\alpha_m r_{1,m}^3 + \beta_m r_{2,m}^3 &= \alpha_{m-1} r_{1,m-1} + \beta_{m-1} r_{2,m-1}^3 & C_{1,m} \\
\alpha_m r_{1,m}^6 + \beta_m r_{2,m}^6 &= \alpha_{m-1} r_{1,m-1}^2 + \beta_{m-1} r_{2,m-1}^2 & C_{2,m} \\
\alpha_m r_{1,m}^9 + \beta_m r_{2,m}^9 &= \alpha_{m-1} r_{1,m-1} r_{1,m-1} + \beta_{m-1} r_{2,m-1} r_{2,m-1} & C_{3,m}
\end{align*}
\]

where, for any natural integer \( m \), \( \alpha_m \) and \( \beta_m \) are scalar constants (real or complex).

Since the graph \( SG^c_{m-1} \) is linked to the graph \( SG^c_m \) by a similar process to the one that links \( SG^c_2 \) to \( SG^c_1 \), one can legitimately consider that the constants \( \alpha_m \) and \( \beta_m \) do not depend on the integer \( m \):

\[
\forall m \in \mathbb{N}^* : \quad \alpha_m = \alpha \in \mathbb{R} , \quad \beta_m = \beta \in \mathbb{R}
\]

The above system writes:

\[
\begin{align*}
\alpha r_{1,m}^3 + \beta r_{2,m}^3 &= \alpha r_{1,m-1} + \beta r_{2,m-1} \\
\alpha r_{1,m}^6 + \beta r_{2,m}^6 &= \alpha r_{1,m-1} r_{1,m-1} + \beta r_{2,m-1} r_{2,m-1} \\
\alpha r_{1,m}^9 + \beta r_{2,m}^9 &= \alpha r_{1,m-1} r_{1,m-1} r_{1,m-1} + \beta r_{2,m-1} r_{2,m-1} r_{2,m-1}
\end{align*}
\]

One has then to consider the following configurations:

i. First case:

For any natural integer \( m \):

\[
r_{1,m} \in \mathbb{R} , \quad r_{2,m} \in \mathbb{R}
\]

and, more precisely:

\[
r_{1,m} < 0 , \quad r_{2,m} < 0
\]

since the function \( \varphi \), which, to any real number \( x \geq 4 \), associates:

\[
\varphi(x) = \frac{2 - x + \varepsilon \sqrt{(x-2)^2 - 4}}{2} , \quad \varepsilon \in \{-1,1\}
\]

is strictly increasing on \([4, +\infty[\). Due to its continuity, is is a bijection of \([4, +\infty[ \rightarrow [1, 0[\).

Let us introduce the function \( \phi \), which, to any real number \( x \geq 2 \), associates:

\[
\phi(x) = |\varphi(x)| = \frac{-2 + x - \varepsilon \sqrt{(x-2)^2 - 4}}{2}
\]

where \( \varepsilon \in \{-1,1\} \).

The function \( \phi \) is a bijection of \([4, +\infty[ \rightarrow [0,1[\). We will denote by \( \phi^{-1} \) its inverse bijection:

\[
\forall x \in [0,1[ : \quad \phi^{-1}(x) = \frac{(y+1)^2}{y}
\]

One has then:
\[ \varphi (\Lambda_{m-1}) = \frac{2 - \Lambda_{m-1} + \varepsilon \omega_{m-1}}{2} \leq 0 \]

This yields:

\[ (-1)^3 (\varphi (\Lambda_m))^3 = \varphi (\Lambda_{m-1}) \leq 0 \]

which leads to:

\[ \phi (\Lambda_m) = (\phi (\Lambda_{m-1}))^{\frac{1}{3}} \]

and:

\[
\Lambda_m = \phi^{-1} \left( (\phi (\Lambda_{m-1}))^{\frac{1}{3}} \right) = \left\{ \frac{(\phi (\Lambda_{m-1}))^{\frac{1}{3}} + 1}{(\phi (\Lambda_{m-1}))^{\frac{1}{3}}} \right\}^2 \left\{ \left( \frac{-2 + \Lambda_{m-1} - \varepsilon \sqrt{\{\Lambda_{m-1} - 2\}^2 - 4}}{2} \right)^{\frac{1}{3}} + 1 \right\}^2
\]

ii. Second case:

For any natural integer \( m \):

\[ r_{1,m} \in \mathbb{C} \setminus \mathbb{R} \quad r_{2,m} = \overline{r_{1,m}} \in \mathbb{C} \setminus \mathbb{R} \]

Let us introduce:

\[ \rho_m = |r_{1,m}| \in \mathbb{R}^+ \quad \theta_m = \arg r_{1,m} \quad \text{if} \quad r_{1,m} \neq 0 \]

The above system writes:

\[
\begin{align*}
\rho_m^3 \{ \gamma \cos (3 \theta_m) + \delta \sin (3 \theta_m) \} &= \rho_{m-1} \{ \gamma \cos (3 \theta_{m-1}) + \delta \sin (3 \theta_{m-1}) \} \\
\rho_m^6 \{ \gamma \cos (6 \theta_m) + \delta \sin (6 \theta_m) \} &= \rho_{m-1}^2 \{ \gamma \cos (6 \theta_{m-1}) + \delta \sin (6 \theta_{m-1}) \} \\
\rho_m^9 \{ \gamma \cos (9 \theta_m) + \delta \sin (9 \theta_m) \} &= \rho_{m-1}^3 \{ \gamma \cos (9 \theta_{m-1}) + \delta \sin (9 \theta_{m-1}) \}
\end{align*}
\]

where \( \gamma \) and \( \delta \) denote real constants.

The system is satisfied if:

\[
\begin{align*}
\rho_m^3 &= \rho_{m-1} \\
\theta_m &= \frac{\theta_{m-1}}{3}
\end{align*}
\]

and thus:

\[ \phi (\Lambda_m) = (\phi (\Lambda_{m-1}))^{\frac{1}{\lambda_0}} \]

which leads to the same relation as in the previous case.
\[
\Lambda_{m} = \phi^{-1}\left(\left(\phi\left(\Lambda_{m-1}\right)\right)^{3}\right) = \left\{\left(\phi\left(\Lambda_{m-1}\right)\right)^{3} + 1\right\}^{2} = \left\{\frac{-2 + \Lambda_{m-1} - \varepsilon \sqrt{\left(\Lambda_{m-1} - 2\right)^{2} - 4}}{2} + 1\right\}^{\frac{1}{3}}^{2} = \frac{-2 + \Lambda_{m-1} - \varepsilon \sqrt{\left(\Lambda_{m-1} - 2\right)^{2} - 4}}{2} + 1
\]

where \( \varepsilon \in \{-1, 1\} \).

5 Detailed study of the spectrum of the Laplacian

As exposed by R. S. Strichartz in [20], one may bear in mind that the eigenvalues can be grouped into two categories:

i. initial eigenvalues, which a priori belong to the set of forbidden values (as for instance \( \Lambda = 2 \));

ii. continued eigenvalues, obtained by means of spectral decimation.

We present, in the sequel, a detailed study of the spectrum of \( \Delta \).

5.1 Eigenvalues and eigenvectors of \( \Delta_{2} \)

Let us recall that the vertices of the graph \( S_{2}^{C} \) are:

\[ X_{j}^{2}, \quad 1 \leq j \leq 10 \]

with:

\[ X_{1}^{2} = A, \quad X_{4}^{2} = B, \quad X_{7}^{2} = C, \quad X_{10}^{2} = A \]

For the sake of simplicity, we will set here:

\[ X_{2}^{2} = E, \quad X_{3}^{2} = F, \quad X_{5}^{2} = G, \quad X_{6}^{2} = H, \quad X_{8}^{2} = I, \quad X_{9}^{2} = J \]

One may note that:

\[ \text{Card } (V_{2} \setminus V_{1}) = 10 - 4 = 6 \]

Let us denote by \( u \) an eigenfunction, for the eigenvalue \( -\Lambda \). Let us set:

\[ u(A) = a \in \mathbb{R}, \quad u(B) = b \in \mathbb{R}, \quad u(C) = c \in \mathbb{R}, \quad u(D) = d \in \mathbb{R} \]

\[ u(E) = e \in \mathbb{R}, \quad u(F) = f \in \mathbb{R}, \quad u(G) = g \in \mathbb{R}, \quad u(H) = h \in \mathbb{R}, \quad u(I) = i \in \mathbb{R}, \quad u(J) = j \in \mathbb{R} \]

One has then:
One may note that the only "Dirichlet eigenvalues", i.e. the ones related to the Dirichlet problem:

\[ u_{|V_1} = 0 \quad \text{i.e.} \quad u(A) = u(B) = u(C) = u(D) = 0 \]

are obtained for:

\[
\begin{align*}
    a + f &= -(\Lambda - 2)e \\
    b + e &= -(\Lambda - 2)f \\
    b + h &= -(\Lambda - 2)g \\
    g + c &= -(\Lambda - 2)h \\
    c + j &= -(\Lambda - 2)i \\
    i + d &= -(\Lambda - 2)j
\end{align*}
\]

i.e.:

\[
\begin{align*}
    f &= -(\Lambda - 2)e \\
    e &= -(\Lambda - 2)f \\
    h &= -(\Lambda - 2)g \\
    g &= -(\Lambda - 2)h \\
    j &= -(\Lambda - 2)i \\
    i &= -(\Lambda - 2)j
\end{align*}
\]

The forbidden eigenvalue \( \Lambda = 2 \) cannot thus be a Dirichlet one.

Let us consider the case where:

\[ (\Lambda - 2)^2 = 1 \]

i.e.

\[ \Lambda = 1 \quad \text{or} \quad \Lambda = 3 \]
which yields a three-dimensional eigenspace. The multiplicity of the eigenvalue $\Lambda = 1$ is 3.

In the same way, the eigenvalue $\Lambda = 3$ yields a three-dimensional eigenspace. the multiplicity of the eigenvalue $\Lambda = 3$ is 3.

Since the cardinal of $V_2 \setminus V_1$ is:

$$\mathcal{N}^S_2 - 4 = 6$$

one may note that we have the complete spectrum.

5.2 Eigenvalues of $\Delta_m$, $m \in \mathbb{N}$, $m \geq 3$

As previously, one can easily check that the forbidden eigenvalue $\Lambda = 2$ is not a Dirichlet one.

One can also check that $\Lambda_m = 1$ and $\Lambda_m = 3$ are eigenvalues of $\Delta_m$.

By induction, one may note that, due to the spectral decimation, the initial eigenvalue $\Lambda_2 = 1$ gives birth, at this $m^{th}$ step, to eigenvalues $\Lambda_{\rightarrow 1,m}$, and, in the same way, the initial eigenvalue $\Lambda_2 = 3$ gives birth, at this $m^{th}$ step, to eigenvalues $\Lambda_{\rightarrow 3,m}$.

The dimension of the Dirichlet eigenspace is equal to the cardinal of $V_m \setminus V_1$, i.e.:

$$\mathcal{N}^S_m - \mathcal{N}^S_1 = 3^m - 3$$

<table>
<thead>
<tr>
<th>Level</th>
<th>Cardinal of the Dirichlet spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>$3^m - 3$</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>78</td>
</tr>
</tbody>
</table>

Property 5.1. Let us introduce:

$$\Lambda = \lim_{m \to +\infty} 3^{-m} 4^m \delta$$

One may note that, due to the definition of the Laplacian $\Delta$, the limit exists.

5.3 Eigenvalue counting function

Definition 5.1. Eigenvalue counting function

Let us introduce the eigenvalue counting function, related to $\mathcal{S}^C \setminus V_1$, such that, for any positive number $x$:

$$\mathcal{N}^{\mathcal{S}^C \setminus V_1}(x) = \text{Card} \{ \Lambda \text{ Dirichlet eigenvalue of } -\Delta : \Lambda \leq x \}$$
Property 5.2. Given an integer $m \geq 2$, the cardinal of $V_m \setminus V_1$ is:

$$N^S_m - N^S_1 = 3^m - 3$$

This leads to the existence of a strictly positive constant $C$ such that:

$$N^{SG^c}(C \cdot 3^{-m} 4^m \delta) = 3^m - 3$$

If one looks for an asymptotic growth rate of the form

$$N^{SG^c}(x) \sim x^{\alpha_{SG^c}}$$

one obtains:

$$\alpha_{SG^c} = \frac{\ln 3}{\delta \ln \frac{4}{3}} = \frac{\ln 3}{\ln 4 - \ln 3}$$

which is not the same value as in the case of the Sierpiński gasket (we refer to [20]):

$$\alpha_{SG} = \frac{\ln 3}{\ln 5 - \ln 3} < \alpha_{SG^c}$$

It appears then that increasing the number of points, and the number of connections, decreases the value of the Weyl exponent $\alpha$.

By following [20], one may note that the ratio

$$\frac{N^{SG^c}(x)}{x}$$

is bounded above and away from zero, and admits a limit along any sequence of the form $C \cdot 3^{-m} 4^m \delta$, $C > 0$, $m \geq 2$. This enables one to deduce the existence of a periodic function $g$, the period of which is equal to $\ln \frac{4^\delta}{3}$, discontinuous at the value $\frac{4^\delta}{3}$, such that:

$$\lim_{x \to +\infty} \left\{ \frac{N^{SG^c}(x)}{x} - g(\ln x) \right\} = 0$$

References


[18] Cl. David et N. Riane, Formes de Dirichlet et fonctions harmoniques sur le graphe de la fonction de Weierstrass, preprint, HAL.


