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A Harmonic Analysis of the Façade of Gaudí's Pedrera

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Abstract
La Pedrera, an emblematic building designed by Antoni Gaudí, is distinguished by the undulating and continuous profile of its façade, thus establishing it as an iconic landmark of Catalan Art Nouveau. The present study proposes a harmonic, descriptive analysis of these undulations, with the aim of exploring their regularity, structure and formal coherence from a mathematical perspective. In order to achieve this objective, high-precision 3D laser scanning techniques and Fourier transform analysis are utilised to disaggregate the geometry of the façade into its constituent frequency components. The results provide a quantitative reading of the undulating rhythm of the surface, revealing harmonic patterns that contribute to understanding the design of the façade from a geometric and systematic approach.

Keywords Antoni Gaudí · La Pedrera · Waves · Fourier transforms

Introduction

La Pedrera, the magnum opus of Antoni Gaudí, is distinguished not only by its architectural significance within the context of Catalan Art Nouveau, but also by the distinctiveness of its undulating façade (Fig. 1). This formal characteristic has long been of interest to architects, historians and artists, although it has rarely been analysed from a rigorously geometric perspective (Asarta 1998; Bassegoda i Nonell 2002; Giralt-Miracle 2002; Salas Mirat et al. 2018).

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Fig. 1 Photograph of La Pedrera, taken in the early twentieth century by Josep Maria Sagarra i Plana. Image: ANC1-585-N-12782. Arxiu Nacional de Catalunya

The present study focuses on the undulations of La Pedrera's façade, with the aim of describing its geometry using harmonic analysis tools (Fig. 2). The central question guiding this study is whether these seemingly free forms respond to some

Fig. 2 Photographs of La Pedrera illustrating the undulations of its façade. Image: authors

kind of underlying regularity, or whether they are the result of artistic intuition without explicit rules. Is the design of these waves arbitrary, or is it possible to identify patterns and principles that reveal a formal coherence? This fundamental question leads to investigate whether there exists an underlying geometric order or design principles, potentially implicit or unconscious to Gaudí, that help explain, at least in part, the visual and spatial coherence that characterises the façade.

It is important to situate this question within the context of Antoni Gaudí's design methodology. His architectural practice was not based on abstract mathematical formulations, but rather on experimental processes combining the use of physical models, geometric intuition, and a close relationship between form, structure, and construction (Giralt-Miracle 2002; Alsina and Nelsen 2025). In many cases, Gaudí employed plaster models and full-scale mock-ups as tools for exploring and verifying the spatial and structural behaviour of his proposals, allowing complex geometries to emerge through iterative and materially grounded procedures (Bassegoda i Nonell 2002). This way of conceiving form brings his architecture closer to processes characteristic of sculptural practice, in which geometry is not defined exclusively through abstract constructions, but emerges through material manipulation and spatial experimentation.

In this sense, the present study does not seek to reconstruct a design method explicitly used by Gaudí, but rather to offer a quantitative interpretation of formal regularities that may underlie the apparent freedom of his architectural language. The proposed harmonic analysis should therefore be understood as an analytical framework capable of revealing possible geometric coherences within the façade, rather than as a direct translation of the original design process.

The originality of this research lies precisely in the application of a contemporary mathematical framework to an architectural object that was not conceived through such methods. Rather than seeking to explain Gaudí's intentions or replace traditional architectural interpretations based on drawing, composition, or historical analysis, the study proposes an alternative geometric reading of the façade. In this sense, the value of the investigation resides in its capacity to reveal formal regularities that remain largely inaccessible through conventional descriptive approaches, thereby opening a complementary perspective on the relationship between architectural form and mathematical order.

In order to address this issue, a mathematical methodology was adopted, based on the acquisition of geometric data using high-precision laser scanning, followed by harmonic analysis using Fourier transform. The presence of undulating behaviour in the primary lines of the façade, particularly evident in the six curved edges delineating its volume (Fig. 3), prompted our decision to interpret these as periodic signals in space, which can be analysed through the application of standard harmonic techniques. The Fourier transform has been extensively applied in the domain of architecture, particularly in the context of acoustic studies (Aygün 2025) and structural analysis (Ivanov and Sato 2024). Additionally, there are notable instances of its utilisation in formal analysis and architectural design (Aygün 2025; Fox and Chung 2024; Puppa et al. 2019).

In summary, this approach will facilitate the proposal of a geometric reading of its design, thereby revealing whether there is a coherent and systematic mathematical structure underlying it.

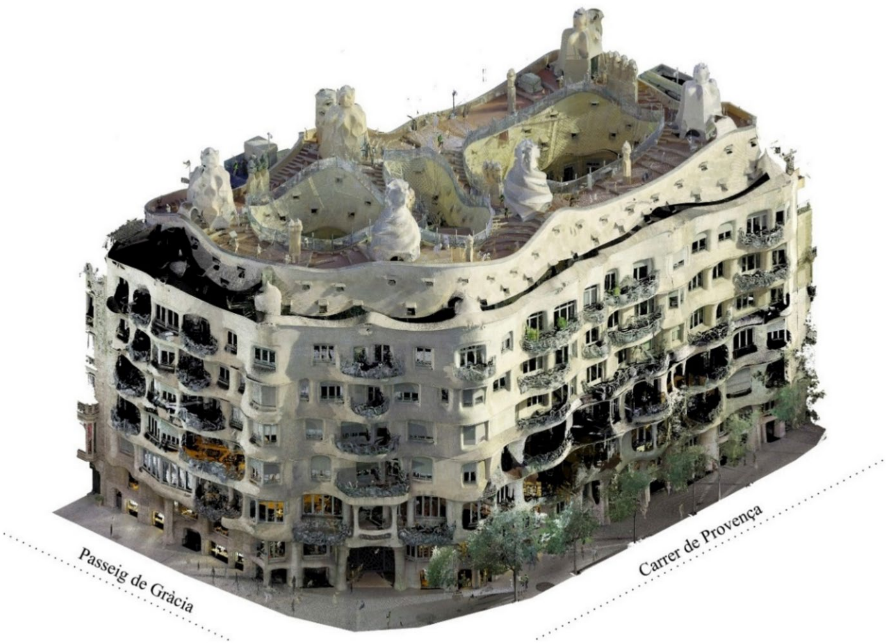

Fig. 3 Three-dimensional reconstruction of the façade of La Pedrera using a Leica RTC 360 laser scanner. Figure created by the authors

Methods

The present study is structured in two main methodological phases. The first phase involves the capture, extraction and geometric representation of the six main curved edges of the façade. These edges are referred to as 'waves' in this study. The second phase involves the harmonic analysis of these edges using Fourier transforms. The initial phase is predicated on high-precision laser scanning and the creation of a detailed digital model of the building. From this model, appropriate horizontal sections are selected in order to determine the edges as discretised curves. In the subsequent phase, these curves are regarded as periodic signals that can be analysed using mathematical frequency analysis tools. The following section details the procedures for geometric acquisition, edge segmentation, generation of associated signals and calculation of their Fourier transforms.

Obtaining and Graphically Representing the Waves

In order to initiate the geometric analysis, it was imperative to accurately capture the three-dimensional shape of the façade. For this purpose, a Leica RTC360 laser scanner was utilised, capable of generating high-fidelity models from real-world data. The survey was conducted using 65 scans, strategically distributed to ensure complete coverage of the architectural front. Specifically, 20 scans were located along Passeig de Gràcia, 35 along Carrer de Provença, and 10 at the chamfered corner of the building.

The data acquisition was not limited to street level, but was complemented by scans performed from elevated positions, including the roof and intermediate levels of the adjacent corner building, in order to improve visibility and reduce occlusions. The methodology and laser scanning survey were developed following established procedures in the specialised literature (Liu et al. 2023).

The resulting high-density point cloud P, composed of approximately five million points, provides a detailed and metrically reliable representation of the façade geometry (Fig. 3). The dataset was processed and registered to ensure geometric consistency, enabling the accurate extraction of the façade traces used in the subsequent analysis.

Following the acquisition of the digital twin of La Pedrera's façade, the six curved waves of the façade will be determined. These waves will be designated W_i, with $i = 1, \dots, 6$ (Fig. 4). For each W_i, it is necessary to extract a point cloud P_i from the global point cloud P of the building. The process is facilitated by the utilisation of Cyclone 3DR software, which employs an algorithm to generate an orthogonal section. This is achieved by centring a 10-cm-thick selection box on the corresponding edge. The height of the box is positioned in such a manner that it encompasses the entire visible length of the curve. This ensures that the cloud P_i accurately contains all the points that geometrically define the wave W_i (Fig. 5).

The selection of the analysed curves responds to their representativeness within the general undulating behaviour of the façade. In particular, those traces

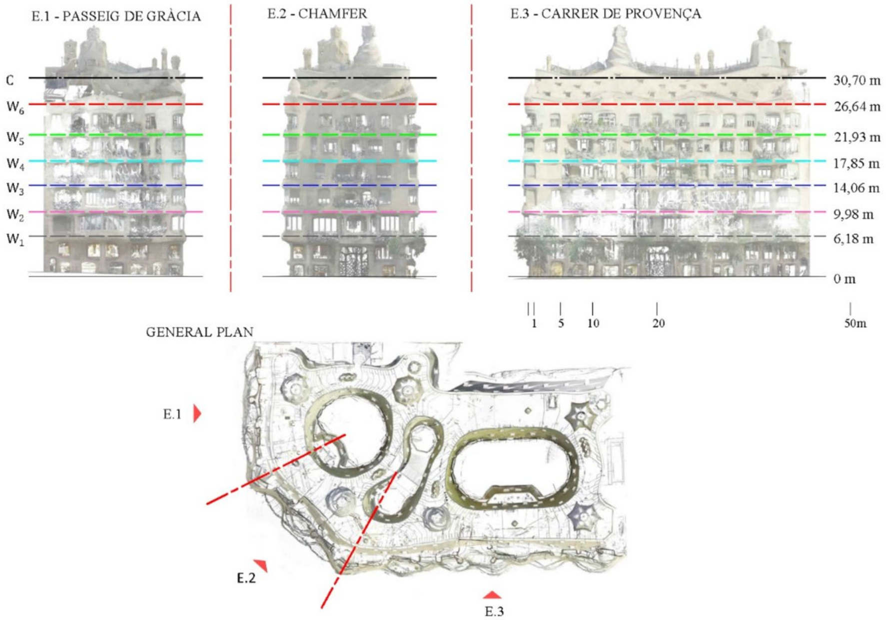

Fig. 4 Developed elevation of the façade, shown in separate sections for each street and the chamfered corner. The various waves, designated W_i, and the cornice, denoted C, are illustrated in colour and with precise locational details. Figure created by the authors

that allow the continuous description of the sequence of waves shaping the built frontage have been considered. Although some of these curves present variations in the vertical direction, the study focuses on their predominant development along the horizontal plane, in order to maintain a homogeneous analysis criterion across all the considered traces.

In this sense, the objective is not to characterise the complete three-dimensional geometry of the architectural envelope, but rather to identify patterns of repetition and regularity in the definition of the waves along the façade.

In order to clarify the relationship between the extracted architectural geometry and the subsequent harmonic analysis, the following conceptual framework is established. The process developed in this study defines a direct correspondence between the built geometry of the façade and its mathematical formalisation. First, the principal undulating edges are obtained from the point cloud generated through laser scanning, ensuring that the analysed curves constitute a faithful representation of the real geometry of the building.

Subsequently, each of these curves is discretised and interpreted as a spatial signal. In this context, the longitudinal position along the cornice acts as the traversal parameter, while the orthogonal deviation of the curve with respect to the longitudinal geometric reference of the cornice is interpreted as amplitude. This transformation does not constitute an arbitrary abstraction, but rather an

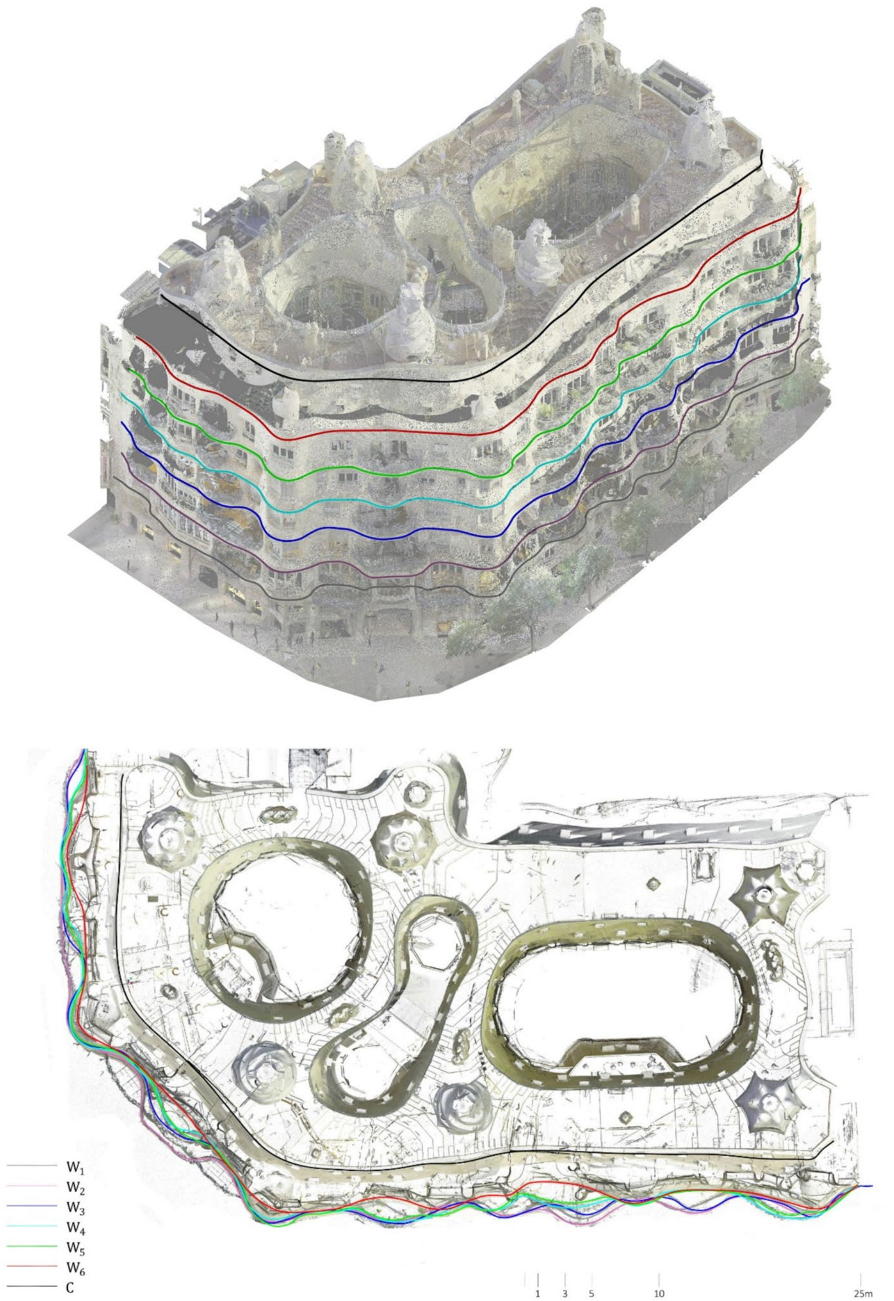

Fig. 5 Plan view of the six waves W_i and the cornice C. The colour code employed in Fig. 4 is also utilised in this instance and throughout the article for each wave. Figure created by the authors

analytical reformulation of the geometry that enables its formal behaviour to be studied quantitatively.

In this way, the application of the Fourier transform makes it possible to decompose these curves into their harmonic components, identifying dominant frequencies that may be interpreted as patterns of repetition or rhythm within the configuration of the façade. Consequently, the mathematical results do not constitute an independent entity, but rather provide a quantitative reading of the underlying geometric logic embedded in the architectural design.

Within this context, the present analysis is based on the extraction and interpretation of traces derived from horizontal sections of the building, allowing the undulating behaviour of the façade to be studied in a controlled and comparable manner, while focusing attention on its predominant development along the horizontal axis. Nevertheless, this methodological choice implies a simplification of the full three-dimensional complexity of the architectural envelope.

In this regard, several studies have addressed the geometric analysis of three-dimensional surfaces through tools based on the Fourier transform, such as the approach proposed by Melzi et al. (2016), which enables the characterisation of spatial geometric variation within three-dimensional domains. In contrast to these approaches, the present study adopts a methodology based on two-dimensional traces, focused on interpreting the predominant undulating behaviour of the façade, thereby allowing the geometric patterns associated with its horizontal development to be isolated and analysed with precision.

Computation of the Fourier Transforms Magnitudes for the Six Waves

In this section, the frequency of the edges W_i is analysed by treating them as waves, with the following design assumptions: (1) the waves are assumed to have been drawn freehand, on paper; (2) each wave is assumed to have been drawn over the same time interval T, given their similar length; and (3) the six waves are assumed to have been drawn following the boundaries of the plot and in compliance with the requirements of the Barcelona City Council at the time the building was designed by Gaudí.

Now, for each W_i, a discrete function f_i is generated with $N = 1000$ values. The function f_i is considered a signal associated with each wave. In other words, for each i, a function $f_i(n)$ is to be generated, where (1)

$$f_i : [0, N-1] \cap \mathbb{Z} \to \mathbb{R} \tag{1}$$

In the following step, the value of period T for all waves W_i is set equal to the length of the cornice curve. The cornice extends along the entire contour of the façade; consequently, in this analysis, the cornice can be regarded as the architectural equivalent of the time interval T. For this reason, a seventh point cloud C is created, corresponding to the edge of the cornice (Fig. 5). This cloud C is obtained in the same manner as the clouds P_i.

Subsequently, the following mathematical steps and digital transformation procedures are performed in order to generate the signals f_i:

(1) The point cloud C of the cornice is projected orthogonally onto the floor plan, thus yielding a flat point cloud C_b and the corresponding two-dimensional coordinates of the points of C_b on the floor plan.

(2) A new point cloud, designated C_s, is generated using Autocad software. This cloud consists of 30,000 points, $C_s = \{p_j\}_{j=0}^{29999}$, and it is a spline curve associated with the cloud C_b. This spline curve is generated in four distinct steps: (1) First, a local density filtering process is applied, removing isolated points or those with low spatial coherence relative to the average density of the point cloud, using an approximate point spacing of 5 mm as the reference threshold. (2) In the second step of the process, two polylines—designated A (inner) and B (outer)—are to be drawn, with the objective of establishing a continuous connection between the points on the inner and outer edges of the cloud C_b. (3) Next, both polylines are subdivided into n equal parts, thereby generating two sets of points on A and B. (4) Subsequently, the midpoint corresponding to each pair of homologous points between A and B is determined, thus obtaining a regular intermediate sequence; (5) In the final step, a spline curve is constructed that interpolates all the midpoints generated. See Fig. 6.

(3) For each wave W_i, the same process is applied to the point cloud P_i as that applied to the cloud C, resulting in a cloud S_i of 30,000 points defining a spline curve for each i.

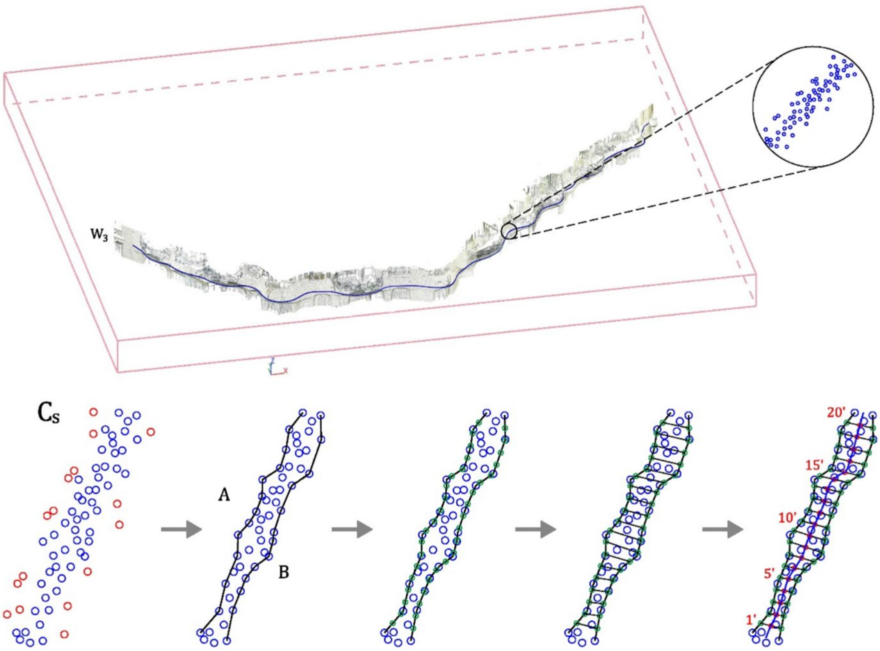

Fig. 6 Workflow for extracting the representative spline from cloud C_s. Figure created by the authors

(4) For an arbitrary i, one of the point clouds S_i is selected. For each point of C_s in position 30 by 30, that is, for each point p_{30k} (with $k = 0, \dots, 999$) of C_s, the following calculation is performed using numerical programming: First, the line n_{30k}, perpendicular to C_s and passing through p_{30k}, is computed. Next, the point $q_{30k} \in S_i$ which is closest to n_{30k} is determined. Finally, the distance $d(p_{30k}, q_{30k})$ is calculated, and the value $f_i(n) = d(p_{30k}, q_{30k})$ is assigned.
(5) The calculation process outlined above is repeated for each of the six clouds S_i, thus yielding the six functions f_i. These are regarded as discrete signals, each associated to the corresponding wave W_i.

The six functions f_i of the six signals which are associated with the six waves W_i are shown superimposed and centered in Fig. 7. The horizontal axis of the graph presents the value of $n \in [0, N-1] \cap \mathbb{Z}$. However, the values of f_i and the scale of the vertical axis are not displayed, as their specific values of signal intensity are not relevant to the conclusions of the study.

(6) For each signal f_i, we consider its Fourier transform $\mathcal{F}\{f_i\} : \mathbb{R} \to \mathbb{C}$, which is a complex 2π-periodic function. To simplify the notation, we write $\mathcal{F}\{f_i\} = \widehat{f_i}$. This transform is defined by (2) and (3):

$$\widehat{f_i} : [-\pi, \pi] \to \mathbb{C} \tag{2}$$

$$\omega \to \widehat{f_i}(\omega) = \sum_{n=0}^{N-1} f_i(n) e^{-i\omega n} \tag{3}$$

The function $\widehat{f_i}$ is defined on $[-\pi, \pi]$ due to its periodicity. Moreover, it is widely acknowledged that this function enables the recovery of the initial function through the following Fourier summation (4):

$$f_i(n) = \frac{1}{N} \sum_{k=0}^{N-1} \widehat{f_i}\left(2\pi \frac{k}{N}\right) e^{i2\pi \frac{k}{N} n} \tag{4}$$

In particular, we consider the real, 2π-periodic, even function corresponding to the magnitude of $\widehat{f_i}$; that is, the function $\left|\widehat{f_i}\right| : \mathbb{R} \to \mathbb{R}$ defined by (5) and (6):

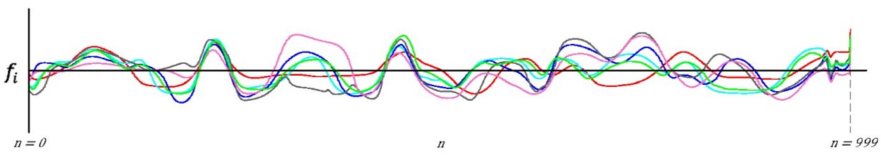

Fig. 7 Superimposition of the six functions f_i corresponding to the signals associated with the six waves W_i. Figure created by the authors

$$\left|\widehat{f_i}\right| : [0,\pi] \to \mathbb{R} \tag{5}$$

$$\omega \to \left|\widehat{f_i}(\omega)\right| = \left|\sum_{n=0}^{N-1} f_i(n)e^{-i\omega n}\right| \tag{6}$$

It is sufficient to define the function $\left|\widehat{f_i}\right|$ on the interval $[0,\pi]$ on account of its periodicity and parity.

Figure 9 shows the superimposed graphs of the magnitudes $\left|\widehat{f_i}\right|$ of the six Fourier transforms. The interval [0, 0.2] is the only one displayed for the six transforms. This is due to the fact that the magnitude is negligible in the remaining interval values and will not have any impact on the study. The corresponding plot of magnitude $\left|\widehat{f_2}\right|$ for wave W_2 is presented individually as an example in Fig. 8.

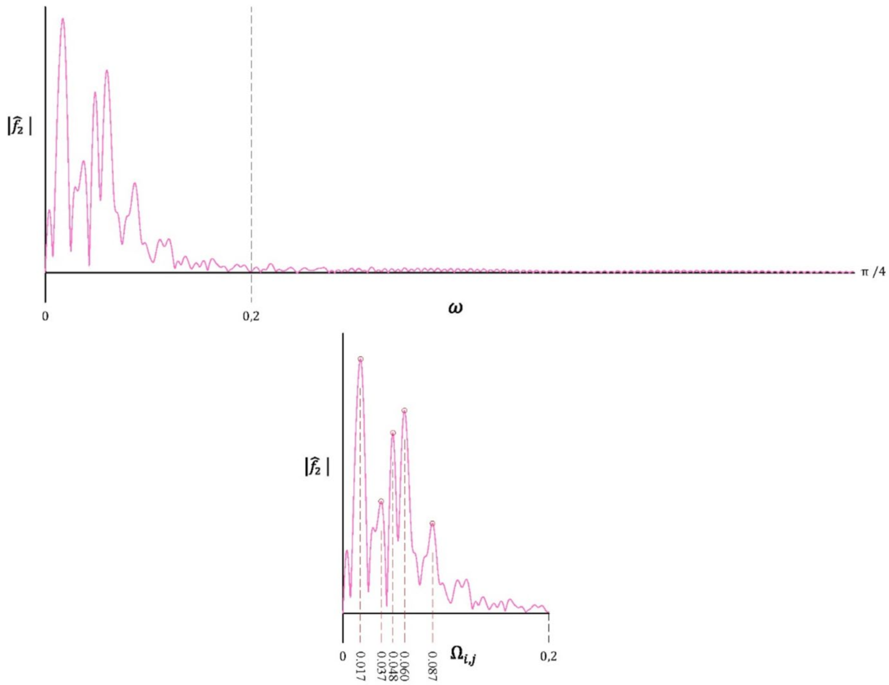

Fig. 8 Plot of the magnitude $\left|\widehat{f_2}\right|$. Figure created by the authors

Harmonic Analysis of Waves

As outlined in the introduction, the objective of this study was to conduct a harmonic analysis of the wave behaviour exhibited by the edges of La Pedrera's façade. In order to accomplish this objective, it is necessary to utilise the dominant frequencies of the waves that have been generated to represent the aforementioned edges. For the purposes of this study, it is sufficient to consider the five frequencies with the highest magnitude.

To identify these five dominant frequencies, the following methodology is employed. Following the procedure outlined in the preceding section, it is possible to accurately reconstruct the signal f_i using the 1000 angular frequencies $\omega_k = 2\pi\frac{k}{N}$. Since we aim to identify the dominant frequencies, we numerically compute, for each $\left|\hat{f}_i\right|$, its five largest local maxima $\{max_{i,j}\}_{j=1}^{5}$ in the interval $[0, \pi]$. This yields, for each signal f_i, its five dominant frequencies $\{\Omega_{i,j}\}_{j=1}^{5}$. Each frequency $\Omega_{i,j}$ corresponds to the abscissa of the respective local maximum $max_{i,j}$ of $\left|\hat{f}_i\right|$. The values have been calculated and are displayed in Table 1 of the results section. The specific case $\{\Omega_{2,j}\}_{j=1}^{5}$ of the wave W_2 is presented graphicallly in Fig. 8. As previously stated, the figures and table do not display the specific values of the maxima, as they are not relevant to the conclusions drawn.

These frequencies $\{\Omega_{i,j}\}_{j=1}^{5}$ are not intrinsic characteristics of the waves W_i, since their values are contingent on the value $N = 1000$ that has been employed for the purpose of discretising. However, the values corresponding to pulses $\mathrm{H}_{i,j}$ generated by each angular frequency value $\Omega_{i,j}$ are indeed characteristic values. For each angular frequency $\Omega_{i,j}$, the corresponding pulse is defined as $\mathrm{H}_{i,j} = \frac{N}{2\pi}\Omega_{i,j}$. If T is defined as one second, this would correspond to a frequency in hertz. Since the actual time T is not known, it is assumed that $\mathrm{H}_{i,j}$ denotes the value of the cycles of the jth angular frequency pulse $\Omega_{i,j}$ of the signal f_i of the wave W_i. The values for the pulses are listed in Table 1 in the following section.

Results and Discussion

As demonstrated in the preceding section, the application of the steps therein resulted in the findings presented in Table 1 below.

The results presented in Table 1 reveal that the six waves exhibit remarkably low dominant angular frequencies, as illustrated in the graph depicted in Fig. 8. It is evident that a common dominant pulse is manifested, as it is observed among the top three with the highest magnitude in each of the six waves. The pulse under discussion emerges with the following six values, which are similar to each other: $H_{1,2} = 7.805$, $H_{2,3} = 7.710$, $H_{3,2} = 7.980$, $H_{4,1} = 8.185$, $H_{5,3} = 7.845$ and $H_{6,1} = 8.240$. The mean of these six similar values of the dominant pulse is $m = 7.961$, and its standard deviation is $\sigma = 0.195$. Therefore, the Pearson

Table 1 Angular frequency $\Omega_{i,j}$ of the 5 dominant pulses for the waves W_i

W_i	Colour	Dominant pulse	$\Omega_{i,j}$	$H_{i,j} = \frac{N}{2\pi}\Omega_{i,j}$
1		1st	0.011	1.685
		2nd	0.049	7.805
		3rd	0.021	3.375
		4th	0.061	9.770
		5th	0.071	11.345
2		1st	0.017	1.715
		2nd	0.060	9.515
		3rd	0.048	7.710
		4th	0.037	5.910
		5th	0.087	13.835
3		1st	0.035	5.520
		2nd	0.050	7.980
		3rd	0.043	6.915
		4th	0.006	0.990
		5th	0.014	2.200
4		1st	0.051	8.185
		2nd	0.036	5.675
		3rd	0.062	9.805
		4th	0.020	3.250
		5th	0.012	1.900
5		1st	0.059	9.425
		2nd	0.019	2.995
		3rd	0.049	7.845
		4th	0.010	1.580
		5th	0.086	13.755
6		1st	0.052	8.240
		2nd	0.036	5.725
		3rd	0.028	4.450
		4th	0.061	9.760
		5th	0.012	1.935

coefficient of variation is $\frac{\sigma}{m} = 0.0245$, representing a value of 2.45%. It is a well-established principle that, when the Pearson coefficient of variation is below 25%, it is indicative of minimal dispersion around the mean. Therefore, in consideration of the Pearson coefficient of variation that has been calculated, it is concluded that the mean value m demonstrates minimal dispersion and is a highly representative metric of the six emerging values of the dominant pulse.

It can thus be concluded that the pulse with a value of $H = 7.961 \simeq 8$ cycles is a harmonic pulse that is highly representative of the six pre-eminent waves of the façade under study. Therefore, this pulse is very representative of the harmonic structure of the façade of Gaudí's Pedrera. Figure 9 shows the superimposed magnitude plots of the Fourier transforms where the position of the value Ω=0.05

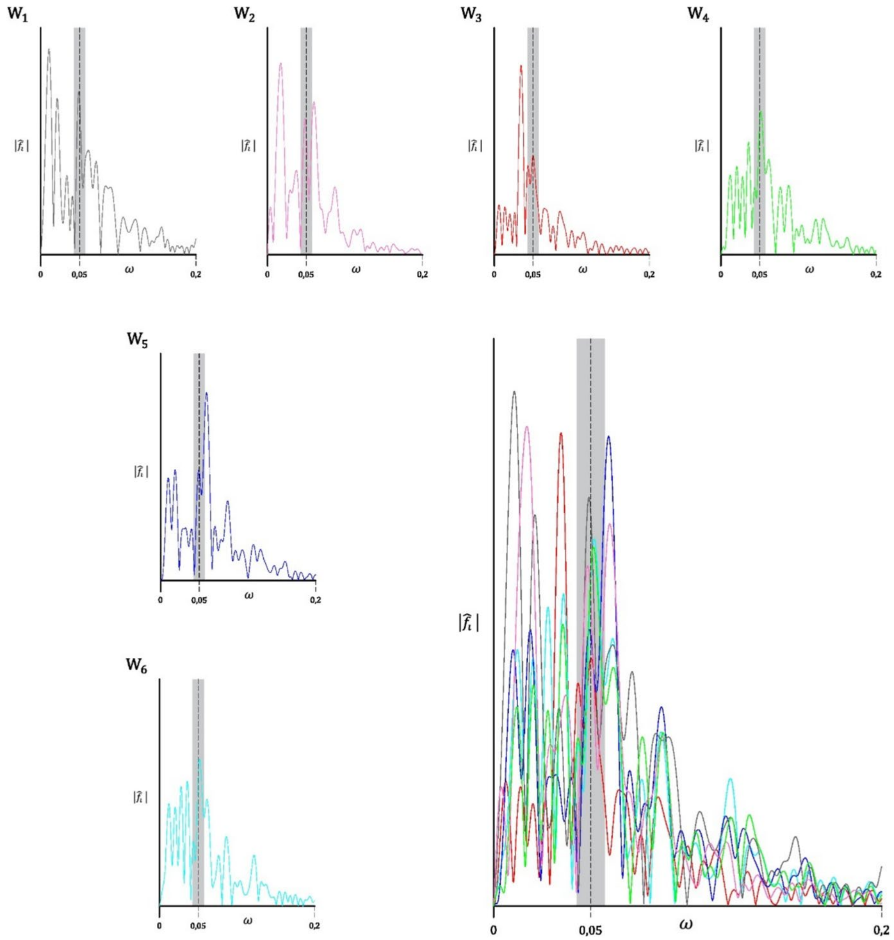

Fig. 9 Superimposed plots of the magnitudes $\left|\hat{f}_i\right|$, with a distinctive colour for each function. The simple harmonic pulse corresponding to $H = 7.961 \simeq 8$ cycles is visually represented by the grey region around the position Ω= 0.05. Figure created by the authors

is marked. This value is associated with the pulse H obtained in our calculations. Looking at the superimposed magnitude plots, it is evident that, at that specific position Ω, H is a pulse common to all of them. This is due to the fact that it is visualised as a sort of common gap in the graphs, an area that has been demarcated in grey and is les rugged than the rest of the superimposition.

From an architectural perspective, the identification of this harmonic pattern allows the façade to be interpreted as a geometric structure characterised by a certain degree of regularity and repetition. The dominant frequencies obtained should not be understood as mere mathematical results, but rather as indicators of a spatial rhythm that organises the continuous perception of the built frontage.

In this sense, the apparent formal freedom of the façade may be reinterpreted as a controlled variation within an underlying system of geometric coherence, in which the repetition, modulation, and continuity of the waves contribute to the formal unity of the whole.

This result should nevertheless be interpreted with caution in relation to Antoni Gaudí's original design process. The identification of a dominant harmonic pattern does not necessarily imply the existence of an explicit design rule formulated in mathematical terms, but may instead be understood as an emergent regularity derived from a process of formal generation based on experimentation and geometric coherence.

In this regard, the analysis carried out does not seek to reconstruct a design procedure historically employed by the architect, but rather to provide a quantitative interpretation capable of revealing possible underlying structures of order within the configuration of the façade. In this way, the results obtained may be interpreted as indicators of rhythm and repetition in the geometric definition of the building, compatible with a non-arbitrary design logic, although not necessarily formulated analytically by its author.

Conclusions

In this study, the tools of harmonic analysis—chiefly the Fourier transform—have been employed to analyse the undulating design of the façade of La Pedrera. The use of a high-resolution digital twin, obtained through terrestrial laser scanning, enabled the extraction and interpretation of the six principal curved edges of the building as spatial signals, thus allowing a quantitative investigation of their geometric behaviour.

The results demonstrate that, despite the apparent formal freedom of the façade, there exists a notable degree of regularity in the wave structure of its edges. In particular, a dominant harmonic pulse has been identified, with an average value of $H = 7.961 \simeq 8$ cycles, consistently present among the principal frequency components of all the analysed signals. This finding supports the existence of an underlying geometric order governing the configuration of the façade (Fig. 10).

From an architectural perspective, this result allows the façade to be interpreted not as an arbitrary composition, but as a controlled variation within a system of geometric coherence. The identified harmonic structure can be understood as an indicator of rhythm, repetition and modulation in the spatial development of the building envelope, contributing to the perceptual unity of the composition.

In this sense, the study provides a quantitative response to the question posed in the introduction: whether the undulating geometry of the façade is arbitrary or governed by identifiable principles. The analysis suggests that these forms follow a consistent harmonic pattern, which may be interpreted as an implicit rule underlying the architectural design. This rule does not necessarily imply a conscious mathematical formulation by Antoni Gaudí, but rather reflects a process of formal generation rooted in geometric coherence and constructive intuition.

Fig. 10 Simple harmonic pulse representative of $H = 7.961 \simeq 8$ cycles around the cornice. Figure created by the authors

More broadly, this work highlights the potential of mathematical tools not as ends in themselves, but as instruments for the interpretation of architectural form. The application of harmonic analysis establishes a dialogue between geometry and perception, offering a framework through which underlying patterns in complex architectural geometries can be identified and understood.

While the present study focuses on a singular case within Gaudí's work—given the unique and continuous nature of the undulating façade of La Pedrera—it is important to note that this condition represents a particular case within the architect's production. Although curved surfaces may also be identified in other works by Gaudí, they generally appear in a localised manner rather than as a dominant generative principle governing the building as a whole.

In this sense, while the proposed methodology may be applicable to other architectural cases, its greatest potential lies in buildings in which undulation or periodic geometric repetition plays a structuring role in the formal definition of the architectural envelope.

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Data availability The data supporting this article are not currently available in a public repository. However, researchers interested in specific data are encouraged to contact the corresponding author, who will consider reasonable requests for access.

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