

Taming a Hydra of Singularities in Fourier Space

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1 Introduction

In [1] Bornemann and Schmelzer invited the reader to contemplate a remarkable limit problem which involves an oscillatory integral of extreme nature. Consider a function $f : \mathbb{R} \rightarrow \mathbb{R}$ that is integrable¹. Does the sequence of violently oscillatory integrals

$$I_n[f] = \frac{1}{\pi} \int_0^\pi f(\tan^{[n]} x) dx, \quad n = 1, 2, 3, \dots, \quad (1)$$

have a limit as n approaches infinity? If so, what is the limit? Here $\tan^{[n]} x = \tan \circ \tan \circ \dots \circ \tan x$ denotes the n -fold iteration of the \tan function.

It is the dramatic behavior of $\tan^{[n]} x$ that inspired Bornemann to call this function the Hydra of singularities. The aggressive nature of this function is revealed already for small n . As x moves from 0 to π , the values of $\tan x$ go all the way from 0 to $+\infty$ and then from $-\infty$ to 0 after passing the singularity at $\pi/2$. The singularity at $\pi/2$ breeds infinitely many new singularities located at x_k where $\tan x_k = (k + 1/2)\pi$ with $k \in \mathbb{Z}$. Note that the values x_k accumulate at $\pi/2$.

This process repeats for each further iteration of \tan . Each singularity breeds countably many new singularities which accumulate in their respective ancestor. In Figure 1 we have tried to illustrate this rather wild behavior of the $\tan^{[n]} x$ iteration.

This paper is a brief companion for the original paper by Bornemann and Schmelzer. The approach taken here could probably be extended for a larger class of functions. This would require a careful analysis shading light away from the central ideas. However, Bornemann and Schmelzer [1] gave already an

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¹A function $f : \mathbb{R} \rightarrow \mathbb{R}$ is integrable if $\int_{-\infty}^{\infty} f(x) dx$ exists. Bornemann and Schmelzer solved the problem for a larger class of functions. In their analysis it was sufficient for f to be bounded and continuous.

elementary proof for a large class of functions and therefore our focus is on a short and elegant analysis using tools from France, in particular Fourier analysis and Cauchy integrals.

2 Into Fourier space and back again

The Fourier transform of f exists but does not have to be integrable. This is an additional requirement for the analysis given here. If both f and its Fourier transform

$$\hat{f}(\xi) := \int_{-\infty}^{\infty} f(x) e^{-2\pi i x \xi} dx, \quad \xi \in \mathbb{R}$$

are integrable then for almost every x (and for all x if f is continuous) f can be represented as the inverse transform of \hat{f}

$$f(x) = \int_{-\infty}^{\infty} \hat{f}(\xi) e^{2i\pi x \xi} d\xi.$$

And therefore

$$f(\tan^{[n]} x) = \int_{-\infty}^{\infty} \hat{f}(\xi) e^{2i\pi \xi \tan^{[n]} x} d\xi.$$

We insert the this term into (1) and restate the problem as

$$I_n[f] = \frac{1}{\pi} \int_0^\pi \int_{-\infty}^{\infty} \hat{f}(\xi) e^{2i\pi \xi \tan^{[n]} x} d\xi dx.$$

Since \hat{f} is integrable the integral

$$\frac{1}{\pi} \int_0^\pi \int_{-\infty}^{\infty} |\hat{f}(\xi) e^{2i\pi \xi \tan^{[n]} x}| d\xi dx$$

exists. We can therefore apply Fubini's theorem and get

$$I_n[f] = \int_{-\infty}^{\infty} \hat{f}(\xi) \frac{1}{\pi} \int_0^\pi e^{2i\pi \xi \tan^{[n]} x} dx d\xi. \quad (2)$$

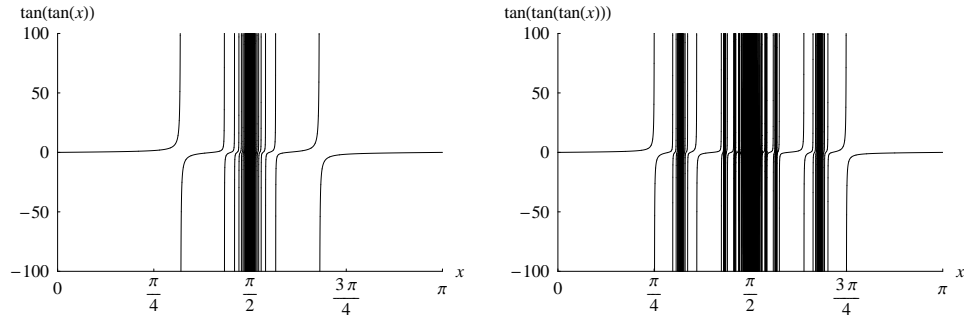


Figure 1: Graph of $\tan^{[2]}(x)$ (left) and $\tan^{[3]}(x)$ (right).

3 The inner Fourier integral

Still the problem does not look any simpler. The Hydra is lurking now in the inner integral

$$\frac{1}{\pi} \int_0^\pi e^{2i\pi\xi \tan^{[n]} x} dx \quad \xi \in \mathbb{R}. \quad (3)$$

The \tan function maps the upper halfplane into itself. Therefore for $\xi \geq 0$ the integrand is bounded in the upper halfplane. We get using dominated convergence

$$\lim_{\epsilon \downarrow 0} \frac{1}{\pi} \int_0^\pi e^{2i\pi\xi \tan^{[n]}(x+\epsilon i)} dx = \frac{1}{\pi} \int_0^\pi e^{2i\pi\xi \tan^{[n]} x} dx \quad \xi \geq 0.$$

The function $e^{2i\pi\xi \tan^{[n]} z}$ is analytic in the upper halfplane and therefore we can apply Cauchy's theorem. As a contour we choose the rectangle with corners $(0, \epsilon i), (\pi, \epsilon i), (\pi, a i), (0, a i)$. The contributions from both vertical vertexes vanish as \tan is periodic. And therefore

$$\lim_{\epsilon \downarrow 0} \frac{1}{\pi} \int_0^\pi e^{2i\pi\xi \tan^{[n]}(x+\epsilon i)} dx = \frac{1}{\pi} \int_0^\pi e^{2i\pi\xi \tan^{[n]}(x+ai)} dx \quad \xi \geq 0, a > 0.$$

Hence we can integrate on any parallel line above the real line. In the extreme case we can move a towards infinity and as

$$\lim_{a \uparrow \infty} \tan^{[n]}(x + ai) = i \tanh^{[n-1]} 1$$

we get

$$\frac{1}{\pi} \int_0^\pi e^{2i\pi \tan^{[n]} x \xi} dx = e^{-2\pi\xi \tanh^{[n-1]} 1} \quad \xi \geq 0.$$

For $\xi \leq 0$ the same argument applied in the lower halfplane yields

$$\frac{1}{\pi} \int_0^\pi e^{2i\pi \tan^{[n]} x \xi} dx = e^{2\pi\xi \tanh^{[n-1]} 1} \quad \xi \leq 0.$$

For $n \rightarrow \infty$ both integrals converge to 1 and hence

$$\lim_{n \uparrow \infty} I_n[f] = \int_{-\infty}^{\infty} \hat{f}(\xi) d\xi = f(0).$$

In the last step we have applied Parseval's theorem.

4 From Fourier to Hardy

Comparing Equation (3) and Equation (1) reveals that the inner Fourier integral is just a special case of (1) with $f(x) = e^{2i\pi\xi x}$. It may seem that we have made use of special properties of this particular function $f(x)$, but in fact the results generalises for a larger class of functions f . To transfer our arguments from

above we need to assume that $f(z)$ is analytic and bounded in the upper half-plane. However, the space of bounded analytic functions in the upper halfplane is the Hardy space H^∞ . So, let $F \in H^\infty$, then $\|F\|_{H^\infty} = \sup_{\text{Im } z > 0} |F(z)| < \infty$. The function f may be interpreted as the non-tangential limit of F , that is $f(x) = F(x + iy)$ for $y \downarrow 0$. This implies f is bounded, too.

Assuming that f is continuous and bounded on the real line this resembles a kind of boundary value problem. However, the analytic extension of f is rarely bounded in the upper halfplane.

Now, from potential theory (see [2, Thms. 15.1a, 15.4d]) we know that there is a function $F(z)$, holomorphic in the upper complex half plane $\text{Im } z > 0$, such that the harmonic function $\text{Re } F(z)$ is bounded and has boundary values given by f , that is,

$$\text{Re } F(x + iy) \rightarrow f(x), \quad x \in \mathbb{R}, \quad (4)$$

as the real number y approaches zero from above. The holomorphic function F is *unique* up to a purely imaginary additive constant. For the sake of simplicity of our presentation, we will further *assume that F itself, not just $\text{Re } F$, is bounded*; this additional assumption will be dropped in the elementary, real analysis proof given in [1].

Therefore

$$\frac{1}{\pi} \int_0^\pi f(\tan^{[n]} x) dx = \text{Re } \frac{1}{\pi} \int_0^\pi F(\tan^{[n]} x) dx = \text{Re } F(i \tanh^{[n-1]} 1).$$

Taking the limit for $n \rightarrow \infty$ reveals:

$$\lim_{n \uparrow \infty} \frac{1}{\pi} \int_0^\pi f(\tan^{[n]} x) dx = f(0).$$

Arguably, there are simpler ways to evaluate f at 0. However, they all lack the drama, brutality and beauty of the Hydra.

References

- [1] Folkmar Bornemann and Thomas Schmelzer, *Taming a hydra of singularities*, Amer. Math. Monthly **114** (2007), no. 8, 727–732.
- [2] Peter Henrici, *Applied and Computational Complex Analysis. Vol. 3*, Wiley, New York, 1986.