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UNIQUE ERGODICITY OF HARMONIC CURRENTS ON SINGULAR FOLIATIONS OF $\mathbb{P}^2$

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Abstract. Let $\mathcal{F}$ be a holomorphic foliation of $\mathbb{P}^2$ by Riemann surfaces. Assume all the singular points of $\mathcal{F}$ are hyperbolic. If $\mathcal{F}$ has no algebraic leaf, then there is a unique positive harmonic $(1,1)$ current T of mass one, directed by $\mathcal{F}$. This implies strong ergodic properties for the foliation $\mathcal{F}$. We also study the harmonic flow associated to the current T.

1 Introduction

Let $\mathcal{F}$ be a holomorphic foliation of the complex projective space $\mathbb{P}^2$. Our purpose is to study the ergodic properties of $\mathcal{F}$, using the theory of harmonic currents as developed by the authors in [FoS].

A holomorphic foliation can be seen as a rational vector field in $\mathbb{C}^2$. Our goal is to develop an ergodic theory for the dynamics of such vector fields. The two main difficulties are: the presence of singularities (they always exist) and the absence (generically) of algebraic leaves. And hence it is not clear where to start the analysis. Our method is geometric but requires difficult estimates. To our knowledge, this is the first paper where global dynamical results for rational vector fields (without invariant algebraic leaves) are obtained. The subject is classical and related to polynomial vector fields in $\mathbb{R}^2$ [LP], [I2].

We first recall a few facts. Let $\pi : \mathbb{C}^3 \setminus \{0\} \to \mathbb{P}^2$ denote the canonical projection. The foliation $\pi^*\mathcal{F}$ can be defined in $\mathbb{C}^3$ by a global 1-form $\omega_0 = a_1(x)dx_1 + a_2(x)dx_2 + a_3(x)dx_3$ where the $a_j(x)$ are homogeneous polynomials of the same degree $\delta \geq 1$, without common factors. Moreover since every line through the origin is in the kernel of ω_0, they satisfy the condition $\sum x_i a_i(x) = 0$

The degree of $\mathcal{F}$ is by definition $\deg \mathcal{F} = d := \deg \delta - 1$. It represents the number of tangencies of a generic line L, with $\mathcal{F}$. Let $\mathrm{Fol}(d)$ denote the space of foliations of degree d. The space of coefficients of 1 forms of degree δ is a projective space. The subspace given by $\sum x_i a_i = 0$ is a linear subspace, so also a projective space. The subspace of 1 forms of degree δ of the form $H\lambda$ where H is a homogeneous polynomial of degree $0 < \delta' < \delta$ and λ is a 1-form of degree $\delta - \delta'$ is an algebraic

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subvariety. This gives that $\mathrm{Fol}(d)$ is the complement of an algebraic subvariety of some $\mathbb{P}^N$.

It follows from the Bézout theorem that the foliation $\mathcal{F}$ has a finite number of singularities bounded uniformly by $\delta^2+\delta+1$. If in a coordinate chart U, $\mathcal{F}$ is defined by $\omega_1 = \alpha(z,w)dz + \beta(z,w)dw$, then $\mathrm{sing}(\mathcal{F}) \cap U = \{\alpha = \beta = 0\}$. We can assume that all the singular points are in the same $\mathbb{C}^2$, $\{p_j = (\alpha_j, \beta_j)\}_{j \le N}$.

Definition 1. Suppose there is a change of coordinates around p_j sending p_j to 0 and such that $\omega_0(z,w) = zdw - \lambda wdz + \mathcal{O}(z,w)^2$ where $\lambda = a+ib$ and b is a nonzero number. We say in this case that the singularity is hyperbolic and that we are in the Poincaré domain.

The following is a classical fact due to Poincaré, see [Ch].

Theorem 1. *Suppose that the singular point is hyperbolic. Then there is a local biholomorphic change of coordinates so that the form ω_0 in these coordinates can be written $\omega_0 = zdw - \lambda wdz$ (with the same λ).*

We remark that the form ω_0 is invariant under scaling except for multiplication by a constant which of course does not affect the zero set. Hence we can assume that the linearization is valid in a fixed large ball, in particular in a neighborhood of the unit bidisc.

The following result is due to Lins Neto–Soares [LiS] (we give only the two-dimensional version, their result is also valid in $\mathbb{P}^k$). The result uses Jouanolou's example of a foliation in $\mathbb{P}^2$ without algebraic leaves, see also [LP].

Theorem 2. *There exists a real Zariski dense open subset $\mathcal{H}(d) \subset \mathrm{Fol}(d)$ such that any $\mathcal{F} \subset \mathcal{H}(d)$ satisfies*

(1) *$\mathcal{F}$ has only hyperbolic singularities and no other singular points.*
(2) *$\mathcal{F}$ has no invariant algebraic curve.*

The global behavior of foliations is not well understood. It is unknown whether every leaf of a given foliation, $\mathcal{F}$, clusters at a singular point. This problem, known as the problem of existence of a minimal exceptional set is discussed in [CLS] and [BoLM] for example. It is conjectured in [I2] that a generic holomorphic foliation by Riemann surfaces in $\mathbb{P}^k$ has dense leaves. Mjuller [M] has constructed non-empty open sets of holomorphic foliations by Riemann surfaces in $\mathbb{P}^2$ such that every leaf is dense. Recently Loray–Rebelo [LoR] have constructed similar examples in $\mathbb{P}^k$.

The dynamical properties of holomorphic foliations in $\mathbb{P}^2$ with the line at infinity invariant have been established by Hudai–Verenov, and Ilyashenko [I1] and [I2].

L. Garnett [G] has introduced the notion of harmonic measure for smooth foliations (without singularities) of a compact Riemannian manifold. She studied their ergodic properties. The article by Candel [Ca] contains a recent approach to that theory. In [FoS] the authors have shown that a $\mathcal{C}^1$ laminated set in $\mathbb{P}^2$, without singularities carries a unique harmonic current of mass 1 directed by the lamination. Very recently Deroin and Kleptsyn [DK] developed the theory of diffusion on transversally conformal foliations and they showed that there are only finitely many harmonic measures. The uniqueness of harmonic measure for the Ricatti equation has been established by Bonatti–Gómez-Mont [BoG]; the ergodic study is continued in Bonatti–Gómez-Mont and Viana [BoGV].

For holomorphic foliations (with singularities) of $\mathbb{P}^2$ the following analogue was proved in [BS]. It is valid for laminations by Riemann surfaces with a small set of singularities, see [BS] and [FoS].

Theorem 3. *Let $\mathcal{F}$ be a holomorphic foliation of $\mathbb{P}^2$. There exists a positive current T on $\mathbb{P}^2$, of bidimension $(1,1)$ and mass 1 which is harmonic, i.e. $i\partial\overline{\partial}T = 0$. Moreover in any flow box B (without singular points), the current can be expressed as*

$$T = \int h_\alpha [V_\alpha] d\mu(\alpha)\,. \tag{1.1}$$

The functions h_α are positive harmonic on the local leaves V_α, and μ is a Borel measure on the transversal. The function $H : B \to \mathbb{R}^+$, $H_{|V_\alpha} = h_\alpha$ is Borel measurable.

Observe that if $\mathcal{F}$ is defined in B by a smooth form ω_0, then $T \wedge \omega_0 = 0$. We will say that the current is directed by $\mathcal{F}$.

A theory of intersection of positive harmonic currents of bidegree $(1,1)$ is developed in [FoS]. The main purpose of the present article is, using that intersection theory, to prove

Theorem 4. *Let $\mathcal{F}$ be a holomorphic foliation in $\mathbb{P}^2$ without algebraic leaves. Assume that all singular points of $\mathcal{F}$ are hyperbolic. Then there is a unique positive harmonic current T of mass one, directed by $\mathcal{F}$.*

A consequence of Theorem 4 and of results from [FoS] is that the foliations $\mathcal{F}$ with only hyperbolic singular points are uniquely ergodic in a very strong sense, i.e. the current T can be obtained by an averaging process on the leaves, whose limit is independent of the leaf. Recall that foliations with only hyperbolic singular points and no invariant algebraic curve don't admit a non-zero directed positive closed current, see for example [FoS, p. 981]. It follows that the leaves are covered by the unit disc Δ. Denote by Δ_r the disc of radius r, centered at zero. We get the following convergence result.

Corollary 1. *Let $\mathcal{F} \in \mathcal{H}(d)$. Let $\phi : \Delta \to L$ be the universal covering of a leaf L. Let $\tau_r := \phi_*\big[\log^+ \frac{r}{|z|}\Delta_r\big]/\big\|\phi_*\big[\log^+ \frac{r}{|z|}\Delta_r\big]\big\|$. Then $\lim_{r\to 1}\tau_r = T$, where T is the unique harmonic current directed by $\mathcal{F}$.*

In section 26, Remark 2, we will show a similar uniqueness result for some classes of foliations with non-hyperbolic singularities.

Observe that under the assumption of Theorem 4 there is no non-zero positive closed current directed by $\mathcal{F}$; see [FoS] and Brunella [Br] for a general discussion of closed cycles for foliations by Riemann surfaces.

A consequence of the above uniqueness result is that there is a unique minimal set with singularities for foliations as in Theorem 4. On that minimal set every leaf is dense. However this does not imply that leaves are dense in $\mathbb{P}^2$. This also does not solve the minimal set problem.

The intersection theory of positive $\partial\overline{\partial}$-closed currents of bidegree (1,1) in [FoS] is valid on compact Kähler manifolds. We just recall a few facts restricting to $\mathbb{P}^2$.

Let T be a positive harmonic current of bidegree $(1,1)$ in $\mathbb{P}^2$, i.e. $i\partial\overline{\partial}T = 0$. Let ω denote the standard Kähler form on $\mathbb{P}^2$. Then T can be written as

$$T = c\omega + \partial S + \overline{\partial S} + i\partial\overline{\partial}u$$

with $c \geq 0$ and S is a $(0,1)$ form such that $S, \partial S, \overline{\partial}S$ are in L^2 and $u \in L^1$. The current $\overline{\partial}S$ depends only on T and is zero only if T is closed. So the quantity $\int \overline{\partial}S \wedge \partial\overline{S}$ which we called energy, measures how far T is from being closed. The expression

$$\int T \wedge T := \int (c\omega + \partial S + \overline{\partial S}) \wedge (c\omega + \partial S + \overline{\partial S})$$

makes sense and is finite. It is independent of the choice of S. Moreover if T_1 and T_2 are two positive harmonic currents such that $\int T_1 \wedge T_2 = 0$, then T_1 and T_2 are proportional $\mathrm{mod}(\partial\overline{\partial}u)$. For currents directed by foliations and whose support does carry a positive closed current, then $\int T_1 \wedge T_2 = 0$ implies that T_1, T_2 are proportional, see [FoS, Lem. 3.10]. On the other hand the currents directed by holomorphic foliations can be expressed in a flow box B as

$$T = \int h_\alpha [V_\alpha] d\mu(\alpha)$$

as described in Theorem 3. It is hence possible to consider the geometric self-intersection of such currents. More precisely consider suitable automorphisms Φ_ϵ of $\mathbb{P}^2$ which are close to the identity. For a current T directed by a foliation $\mathcal{F}$, it is possible to define the geometric intersection $T \wedge_g \Phi_{\epsilon *}(T)$ as the measure on the complement of the singular points given locally by the expression

$$\int \Big[\sum_{p \in J^\epsilon_{\alpha,\beta}} h_\alpha(p) h^\epsilon_\beta(p) \delta_p \Big] d\mu(\alpha) d\mu(\beta) . \tag{1.2}$$

Here $J^\epsilon_{\alpha,\beta}$ denotes the points of intersection of the plaque L_α and the plaque $(\Phi_\epsilon)_* L_\beta$ and δ_p denotes the Dirac mass at p. It is shown in [FoS] that $\int T_1 \wedge T_2 = \lim_{\epsilon\to 0} \int T_1 \wedge_g T_{2,\epsilon}$ ([FoS, Lem. 19]). To show that $\int T_1 \wedge T_2 = 0$ it is enough to count the number of points of intersection of a given plaque with perturbed plaques and estimate the harmonic functions. This is done in [FoS, Th. 6.2] when we assume that the currents T_1, T_2 are supported on a minimal laminated compact set, which is transversally of class $\mathcal{C}^1$.

Indeed the minimality hypothesis is not used and the argument there gives the following stronger result.

Theorem 5. *Let $\mathcal{F}$ be a $\mathcal{C}^1$ lamination with singularities by Riemann surfaces in $\mathbb{P}^2$. Assume that there is a laminated compact set X without singularities. Then there is a unique positive harmonic current T, of mass 1, directed by $\mathcal{F}$.*

Proof. We know that there is a harmonic current T_1 of mass 1, supported on X. Let T_2 be another such current directed by $\mathcal{F}$, but not necessarily supported by X. The argument in [FoS, Th. 6.2] shows that $\lim_{\epsilon\to 0} \int T_1 \wedge_g T_{2,\epsilon} = 0$. Hence $\int T_1 \wedge T_2 = 0$. Therefore T_1 and T_2 are proportional. □

We now deal with the case where the foliation is holomorphic and the current T contains in its support singular points (which are all hyperbolic).

We will prove the following more general result than Theorem 4.

Theorem 6 (Main Theorem). *Let $\mathcal{F}$ be a holomorphic foliation of $\mathbb{P}^2$ without algebraic leaves. Let X be a closed invariant set for $\mathcal{F}$. Assume that all singular points of X are hyperbolic. Then there is a unique positive harmonic current T of mass 1, directed by X.*

The result is valid for a laminated set $(X, \mathcal{L}, E)$ where $X \setminus E$ is a $\mathcal{C}^1$ lamination by Riemann surfaces. The set $E = \{p_1, \dots, p_\ell\}$ is a finite set and in a neighborhood U_j of every singular point p_j we assume that $X \cap U_j$ is holomorphically equivalent to a lamination contained in $z = Cw^{\lambda_j}$, $\lambda_j = a_j + ib_j$, $b_j \neq 0$. One of the consequences of the main theorem is Corollary 3 (section 26) which says that appropriate weighted averages of the leaves always converge to the current T. This is a strong ergodic theorem. The uniqueness of T also permits to show that $\lambda \to T_\lambda$ is continuous when λ varies in a holomorphic family of foliations as considered in the main theorem.

It is easy to see that $\overline{\partial} T = \overline{\tau} \wedge T$, τ is a $(1,0)$ form along leaves. We consider in section 27 a metric $g_T := \frac{i}{2} \tau \wedge \overline{\tau}$ and we show that the curvature κ of that metric satisfies $\kappa(g_T) = -1$. We also define a finite measure $\mu_T := i\tau \wedge \overline{\tau} \wedge T$. We have that the measures vary continuously with the foliation. The metric g_T and the measure μ_T were introduced by S. Frankel [Fr] in the nonsingular case. Candel, Gómez-Mont and Glutsyuk have given good criteria for the conformal type of leaves for singular foliations see [CaG] and [Gl].

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2 Sketch of Proof of the Main Theorem

Let T be a harmonic current of mass 1 supported on X and directed by $\mathcal{F}$. In a flow box

$$T = \int h_\alpha [V_\alpha] d\mu(\alpha) .$$

We have to estimate the number of intersection points of a plaque with perturbed plaques near a singularity and also to study the behaviour of the harmonic continuation $\tilde{h}_\alpha$ of h_α along a leaf near a hyperbolic singularity.

This will give us that the geometric intersection is zero and hence $\int T \wedge T = 0$. Since T is arbitrary, the intersection theory of positive harmonic currents and the nonexistence of a closed current imply that T is unique.

After a change of coordinates we do the analysis for the form $\omega_0 = zdw - \lambda w dz$, $\lambda = a + ib$, $b \neq 0$, near $(0,0)$.

In order to study positive harmonic currents near 0, we cover a deleted neighborhood of 0 by finitely many "flow boxes" $(B_i)_{1 \le i \le N}$, with $0 \in \overline{B_i}$ for every i. Each $B_i = S_i \times \Delta$, where S_i is a sector in $\mathbb{C}$ such that the map $\zeta \to e^\zeta$ is injective in a strip in the ζ-plane $\gamma_1 < \Im \zeta < \gamma_2$, with values in S_i, Δ is a disc in $\mathbb{C}$, centered at 0. So the leaves in B_i are graphs over all or part of S_i. We will consider them as the local plaques. For the sake of argument we will use the sector S given by $0 < u < 2\pi$.

The strategy for the proof is to choose a family of automorphisms (Φ_ϵ) of $\mathbb{P}^2$, close to the identity and to estimate the integral (1.2) in the flow boxes $(B_i)_{i\le N}$. For that purpose we need to estimate the growth of the harmonic continuation of h_α along the leaves and also the number of intersection points of a plaque L_α, with perturbed plaques L^ϵ_β.

Away from singularities this is just the proof given in [FoS] for a lamination. In the present case we have to divide the phase space into many regions where the estimates are technically different. The estimates are different close to separatrices and in other regions. This requires a precise subdivision of a polydisc near a singular point. We will describe the subdivision in more detail after stating Theorem 7.

Consider again the foliation $zdw - \lambda wdz = 0$, $\lambda = a + ib$, $b \neq 0$. Notice that if we flip z and w, we replace λ by $1/\lambda = \overline{\lambda}/|\lambda|^2 = a/(a^2+b^2) - ib/(a^2+b^2)$. We will assume below that the axes are chosen so that $b > 0$. However, it is important to note that the estimates are also valid if $b < 0$. The point is that it will be seen that the case $a = 1$ is a degeneracy that complicates the estimates. However if we flip coordinates, the constant $a = 1$ becomes $a/(a^2+b^2) = 1/(1+b^2) < 1$. We now describe a general leaf.

There are two separatrices, $(w = 0), (z = 0)$. Other than that a leaf L_α can be parametrized by $(z, w) = \psi_\alpha(\zeta)$, $z = e^{i(\zeta+(\log|\alpha|)/b)}$, $\zeta = u+iv$, $w = \alpha e^{i\lambda(\zeta+(\log|\alpha|)/b)}$. We have $|z| = e^{-v}$, $|w| = e^{-bu-av}$.

Notice that as we follow z once counterclockwise around the origin, u increases by 2π, so the absolute value of $|w|$ decreases by the multiplicative factor of $e^{-2\pi b}$. Hence we cover all leaves by restricting the values of α so that $e^{-2\pi b} \le |\alpha| < 1$. We observe that with the above parametrization, the intersection with the unit bidisc of the leaf is given by $v > 0$, $u > -av/b$ independently of α. In the (u, v)-plane this corresponds to a sector $S = S_\lambda$ with corner at 0 and given by $0 < \theta < \arctan(-b/a)$ where the arctan is chosen to have values in $(0, \pi)$. Let $\gamma := \frac{\pi}{\arctan(-b/a)}$. Then the map $\phi : \tau \to \tau^\gamma$ maps this sector to the upper half plane with coordinates (U, V). The fact that $\gamma > 1$ will be crucial, this is where the hyperbolicity of singularities is used.

Let h_α denote the harmonic function associated to the current T on the leaf L_α. The local leaf clusters on both separatrices. To investigate the clustering on the z-axis, we use a transversal $D_{z_0} := \{(z_0, w); |w| < 1\}$ for some $|z_0| = 1$. We can normalize so that $h_\alpha(z_0, w) = 1$ where (z_0, w) is the point on the local leaf with $e^{-2\pi b} \le |w| < 1$. So $(z_0, w) = \psi_\alpha(\zeta_0) = \psi_\alpha(u_0 + iv_0)$ with $v_0 = 0$ and $0 < u_0 \le 2\pi$ determined by the equations $|z_0| = e^{-v_0} = 1$ and $e^{-2\pi b} \le |w| = e^{-bu_0-av_0} < 1$. Let $\tilde{h}_\alpha$ denote the harmonic continuation along L_α. Define $H_\alpha(\zeta) := \tilde{h}_\alpha\big(e^{i(\zeta+(\log|\alpha|)/b)}, \alpha e^{i\lambda(\zeta+(\log|\alpha|)/b)}\big)$ on S_λ.

Proposition 1. *The harmonic function $\tilde{H}_\alpha := H_\alpha \circ \phi^{-1}$ is the Poisson integral of its boundary values. So in the upper half plane $\{U + iV; V > 0\}$,*

$$\tilde{H}_\alpha(U + iV) = \frac{1}{\pi}\int_{-\infty}^{\infty} \tilde{H}_\alpha(x)\frac{V}{V^2 + (x-U)^2}dx \tag{2.1}$$

[for $d\mu$ a.e. α]. Moreover,

$$\int_{e^{-2\pi b}\le|\alpha|<1}\int_{-\infty}^{\infty}\tilde H_\alpha(x)|x|^{\frac{1}{\gamma}-1}dx\,d\mu(\alpha)<\infty\,. \tag{2.2}$$

Proof. Let $A_n := \{(z_0,w); e^{-2\pi b(n+1)} \le |w| < e^{-2\pi bn},\ n=0,1,\dots\}$. The holonomy map around $(z=0)$ as described above gives a map

$$A_n \to A_{n+1}\,.$$

The transverse masses of these sets are $\int_{A_0} H_\alpha(\zeta_0+2\pi n)d\mu(\alpha) = B_n(\zeta_0)$. The functions $B_n(\zeta)$ are harmonic on $\{v>0, u>-av/b-2\pi n\}$. Since the transverse mass is finite on $(z=z_0)$ and since the annuli A_n are disjoint we get,

$$\sum_{n=0}^{\infty} B_n(\zeta_0)<\infty\,. \tag{$*$}$$

We get a similar estimate along the other separatrix. It follows that

$$\int_{A_0}\left(\int_{\partial S_\lambda} H_\alpha\right)d\mu(\alpha)<\infty\,. \tag{2.3}$$

We show now that for almost every α, $\tilde H_\alpha(x,y)$ is equal to the Poisson integral of its restriction to $y=0$. Every positive harmonic function on the upper half plane can be written as a sum of a Poisson integral and cy, $c\ge 0$. The problem is to show that $c=0$.

We consider the restriction L'_α of L_α to the bidisc $\Delta^2(0,e^{-1})$. The leaf L'_α equals $\psi_\alpha(S'_\lambda)$ where $S'_\lambda := \{v>1, u>-av/b+1/b\}$. The image of this sector under ϕ is a domain of the form $\Delta'_{\lambda,\alpha} = \{x+iy; y>\gamma_\alpha(x)\}$ where γ_α is a continuous strictly positive function so that $\gamma_\alpha\to+\infty$ when $|x|\to\infty$. The function B_1 is bounded on the edges of S'_λ. So $\tilde B_1 := B_1\circ\phi^{-1}$ is bounded on the graph of γ_α and hence there is no term cy, $c>0$, in the canonical representation of $\tilde B_1$. The same argument is valid for the functions $\tilde H_\alpha$ at least for μ almost every α.

It follows that the representation as a Poisson integral is valid. On the other hand, estimate (2.3) can be read as

$$\int_{e^{-2\pi b}\le|\alpha|<1}\int_0^{\infty} H_\alpha(u)du\,d\mu(\alpha)<\infty \quad\text{and}$$

$$\int_{e^{-2\pi b}\le|\alpha|<1}\int_0^{\infty} H_\alpha\big(ue^{i\arctan(-b/a)}\big)du\,d\mu(\alpha)<\infty\,,$$

which, after a change of variables, gives the estimates (2.1) and (2.2) on the growth of $\tilde H_\alpha$. □

COROLLARY 2. *Let $\mathcal F$ be a foliation as in Theorem 6. Then for any positive harmonic current T, directed by $\mathcal F$, the transverse measure μ is diffuse.*

Proof. Assume μ has an atomic part, i.e. a Dirac mass at p. Let L be the leaf through p. The restriction T to L is a non-zero positive harmonic current. We can normalize so that the transverse measure is one. Then we have a positive harmonic function h defined on L.

If there is a flow box B, away from the singularities, such that L crosses B on infinitely many plaques on which h is bounded below by a strictly positive constant, then we get a contradiction because the mass of T should be finite. In any flow box the leaf must intersect in infinitely many plaques P_j and the harmonic functions $h_j = h_{|P_j}$ must go uniformly to zero as $j \to \infty$.

Let f denote the lifting of the harmonic function to the unit disc, so $f = h \circ \phi$ where $\phi : \Delta \to L$ is a universal covering map. Since $f > 0$ there is a set $S \subset \partial\Delta$ of full measure on which f has nontangential limits $f(e^{i\theta})$.

Lemma 1. *The function $f(e^{i\theta}) = 0$ a.e. on S.*

Proof. Suppose that $f(e^{i\theta_0}) > 0$, $\theta_0 \in S$. We consider the curve $\phi(re^{i\theta_0})$. By the above argument, it follows that this curve can only intersect finitely many plaques in any flow box away from the singular points. But if some plaque is visited infinitely many times as $r \to 1$, we see that h must be constant on this plaque, hence constant on the leaf, a contradiction. It follows that the curve converges to a singular point.

Then it follows from [FoS, p. 991] that this only happens on a set of measure 0, because almost every radius leaves some ball around the singularity. □

A consequence of the lemma is that the function f is given by the convolution of the Poisson kernel with a singular measure. This implies that the function f is unbounded. Outside any given neighborhood of the singular set the function must be uniformly bounded. But then the Poisson integrals of Proposition 1 are also uniformly bounded. Hence by Proposition 1 the function is uniformly bounded everywhere, a contradiction. □

Remark 1. It is convenient in some later calculations to replace $|x|^{1/\gamma-1}$ by $(|x|+1)^{1/\gamma-1}$ in the integral of Proposition 1. By Harnack, this doesn't effect the order of magnitude of the integral.

We decompose a leaf L_α into plaques $L_{\alpha,n}$ where $2n\pi < u < 2(n+1)\pi$. Here n is an integer. [Note that if $a \leq 0$, these n must be positive to have a nonempty intersection with the bidisc.] In this way $L_{\alpha,n}$ is a graph over some part of the z-axis.

We let (z, w) be a point in L_α parametrized by a point (u, v). We write in polar coordinates, $u + iv = \rho e^{i\theta}$ with $\rho = \sqrt{u^2+v^2}$, $\theta = \arctan(v/u)$. Then in the (U, V) plane this point corresponds to $U + iV = \phi(u + iv) = (u + iv)^\gamma$,

$$U + iV = \rho^\gamma e^{i\gamma\theta} = \rho^\gamma \cos(\gamma\theta) + i\rho^\gamma \sin(\gamma\theta)\,.$$

We hence get the following formula for the function $H_\alpha(u + iv)$.

Lemma 2.

$$H_\alpha(u+iv) = \frac{1}{\pi}\int \tilde{H}_\alpha(x)\frac{\rho^\gamma \sin(\gamma\theta)}{(\rho^\gamma \sin(\gamma\theta))^2 + (x-\rho^\gamma\cos(\gamma\theta))^2}\,dx\,. \tag{2.4}$$

Now we write the formula for the perturbed foliation $\mathcal{F}_\epsilon = (\Phi_\epsilon)_*\mathcal{F}$ where Φ_ϵ is a family of automorphisms of $\mathbb{P}^2$. We will need as in [FoS] that all our estimates stay valid when composing Φ_ϵ with Ψ in a neighborhood of the identity in $U(3)$ (depending on ϵ). We will need that Φ_ϵ moves the singular point in a direction away from the separatrices near all the hyperbolic points. We also need the Φ_ϵ to have a common fixed point p in the support of T and that the tangent space of the leaf through p moves to first order with ϵ. So we write in $\mathbb{C}^2$

$$\Phi_\epsilon(z,w) = \big(\alpha(\epsilon),\beta(\epsilon)\big) + (z,w) + \epsilon\mathcal{O}(z,w)$$

with $\alpha'(0),\beta'(0) \neq 0$. We will also need that $\lambda \neq \beta'(0)/\alpha'(0)$.

Suppose that (z,w) is a point in the perturbed bidisc $\Phi_\epsilon(\Delta^2)$, not on a separatrix of $\mathcal{F}_\epsilon$. Then $\Phi_\epsilon^{-1}(z,w)$ is on some plaque $L_{\beta,m}$ with parameters (u',v'). We ignore the problem that we need $u' \neq 2\pi$ because we can also use other flow boxes. The original point (z,w) is on a plaque $L^\epsilon_{\beta,m}$ and we get

Lemma 3.

$$H^\epsilon_\beta(u'+iv') = \frac{1}{\pi}\int \tilde{H}^\epsilon_\beta(y)\frac{(r')^\gamma\sin(\gamma\theta')}{((r')^\gamma\sin(\gamma\theta'))^2 + (y-(r')^\gamma\cos(\gamma\theta'))^2}dy\,. \tag{2.5}$$

Next, for each $(\alpha,\beta,m,n,\epsilon)$, let $I_{\alpha,\beta,m,n,\epsilon}$ denote the set of points p in a slightly smaller bidisc which belong to $L_{\alpha,n}\cap L^\epsilon_{\beta,m}$. Our main technical result is the following Theorem,which says that the geometrical intersection is zero, so that the current T is unique, see section 26.

Theorem 7.

$$\lim_{\epsilon\to 0}\int\sum_{m,n}\sum_{p\in I_{\alpha,\beta,m,n,\epsilon}}\tilde{h}_{\alpha,n}(p)\tilde{h}^\epsilon_{\beta,m}(p)d\mu(\alpha)d\mu(\beta) = 0\,.$$

Proof. During the proof it will be convenient to divide up the region of integration into several pieces. For constants $0 < c < C$ and $\delta > 0$, we consider the regions around one of the finitely many singular points.The regions are defined as follows:

$$D_1 = \big\{(z,w)\,;\ |z| \leq c\epsilon\,,\ |w| \leq c\epsilon\big\}$$
$$D_2 = \big\{(z,w)\,;\ |z| \leq C\epsilon\,,\ |w| \leq C\epsilon\big\}\setminus D_1$$
$$D_3 = \big\{(z,w)\,;\ |z| \leq \delta\,,\ |w| \leq \delta\big\}\setminus D_1\cup D_2\,.$$

By [FoS], for any given $\delta > 0$, the contribution to the integral from outside these regions goes to zero when $\epsilon \to 0$, this uses that the measure is diffuse. We will subdivide the regions D_1, D_2, D_3 further. For most of these new subregions the contributions go to zero with ϵ. But for some of the subregions, we need δ to go to zero for the contribution to go to zero. Hence in the following arguments, δ will be an unspecified small number which will later go to zero. So the way the argument works is, in order to show that the integral becomes smaller than some given $\tau > 0$ when $\epsilon \to 0$, we first fix a very small δ and then let $\epsilon \to 0$. This is the case at the end of sections 8, 9. We will constantly use the finiteness of the integral in Proposition 1, in order to show that the limits are zero.

The constants c and C are determined by the geometry of the leaves near the singularity. We choose $c > 0$ small enough that the region D_1 does not contain the singular point of the perturbed foliation. In fact we will make $c > 0$ so small that the slopes of the leaves of the perturbed foliation are almost constant on D_1. The precise estimate is done in Lemma 4.

For the constant C we want to make sure that the singular point of the perturbed foliation is inside $\Delta^2(0, C|\epsilon|/2)$. So for example the choice $C = 3\max\{|\alpha'(0)|, |\beta'(0)|\}$ will work.

3 Proof of Theorem 7 for the intersection points in D_1 (close to the singularity)

LEMMA 4. *Let $\delta > 0$. Then for all small enough c, $|\epsilon|$, the slopes of the leaves of $\mathcal{F}_\epsilon$, $\frac{dw}{dz} \in \Delta\big(\lambda\frac{\beta'(0)}{\alpha'(0)};\delta\big)$ at all points in D_1.*

Proof. Recall that

$$\Phi_\epsilon(z,w) = \big(\alpha(\epsilon),\beta(\epsilon)\big) + (z,w) + \epsilon\mathcal{O}(z,w)\,.$$

We estimate ω_ϵ, the form defining $\mathcal{F}_\epsilon$ in D_1. We have

$$\begin{aligned}\omega_\epsilon &:= (\Phi_\epsilon)_*(\omega_0)\\ &= \mathcal{O}(\epsilon^2) + \big[(z-\alpha(\epsilon))(1+A\epsilon) + B\epsilon(w-\beta(\epsilon))\big]dw\\ &\quad + \big[(z-\beta(\epsilon))(-\lambda + C\epsilon) + D\epsilon(z-\alpha(\epsilon))\big]dz\\ &= \mathcal{O}(\epsilon^2) + \big(z-\alpha(\epsilon)\big)dw + \big(z-\beta(\epsilon)\big)(-\lambda)dz\\ &= \big(z-\alpha'(0)\epsilon + \mathcal{O}(\epsilon^2)\big)dw - \lambda\big(w-\beta'(0)\epsilon+\mathcal{O}(\epsilon^2)\big)dz\,.\end{aligned}$$

So,

$$\frac{dw}{dz} = \frac{\lambda(w-\beta'(0)\epsilon+\mathcal{O}(\epsilon^2))}{z-\alpha'(0)\epsilon+\mathcal{O}(\epsilon^2)} = \lambda\frac{\beta'(0)}{\alpha'(0)} + \cdots$$

The lemma follows immediately. □

The following lemma describes the lamination associated to $\omega_\epsilon = (\Phi_\epsilon)_*(\omega_0)$ near D_1 after possibly shrinking c further and is an immediate consequence of Lemma 4.

LEMMA 5. *The plaques of $\mathcal{F}_\epsilon$ near D_1 are of the form $w = f_\eta(z)$ where $f_\eta(\eta) = 0$ and $f'_\eta \in \Delta\big(\lambda\frac{\beta'(0)}{\alpha'(0)};\delta\big)$.*

To estimate the geometric wedge product we will consider three types of points in a plaque $L^\epsilon_{\beta,m}$, namely if they are close to where the plaque crosses the z-axis (Case 1) or w-axis or otherwise (Case 2). The estimates for $\tilde{h}^\epsilon_\beta$ are fairly independent of which case we are in because of the choice of c, but h_α is very sensitive to the cases.

We estimate the function $\tilde{h}^\epsilon_\beta$ on these plaques. First observe that the points in $B_2 := \Delta^2((-\alpha'(0)\epsilon, -\beta'(0)\epsilon); 2c|\epsilon|)$ are mapped by Φ_ϵ to a region covering D_1.

LEMMA 6. *There is a constant $C > 0$ so that if some leaf L^ϵ_β intersects D_1 for a parameter value $u + iv$ then*

$$\frac{1-a}{b}\log\big(1/|\epsilon|\big) - C < u < \frac{1-a}{b}\log\big(1/|\epsilon|\big) + C\,, \tag{2.6}$$

and

$$\log\big(1/|\epsilon|\big) - C < v < \log\big(1/|\epsilon|\big) + C\,. \tag{2.7}$$

Proof. First recall that $z = e^{i(u+iv+(\log|\beta|/b))}$. Hence $|z| = e^{-v}$. But $(z,w) \in B_2$. Hence

$$\big(|\alpha'(0)| - 2c\big)|\epsilon| < |z| = e^{-v} < \big(|\alpha'(0)| + 2c\big)|\epsilon|\,.$$

So

$$\log|\epsilon| - C < -v < \log|\epsilon| + C$$

which gives the estimate on v.

The inequalities for u follow also by a straightforward manipulation. □

In what follows we use the notation $A \sim B$ to mean that there is a constant L so that $\frac{1}{L}A \leq B \leq LA$ and L is chosen independent of the other parameters. Also $A \lesssim B$ means similarly that there is a constant L so that $A \leq LB$.

Next we estimate the value of $\tilde{h}^\epsilon_\beta$ for a point (u, v) as in the previous lemma. Let θ, $\tan\theta = v/u$ be the argument. By Lemma 6, it follows that, for all small ϵ, $\tan\theta \sim b/(1-a) \neq b/(-a)$ so that the angle θ is uniformly inside the sector S_λ for all small ϵ. It follows that $\gamma\theta$ is strictly inside a sector $0 < s < \gamma\theta < \pi - s < \pi$ for some fixed $s > 0$ which only depends on λ and is independent of all other choices, and for all small enough ϵ. This implies that $\sin\gamma\theta > k > 0$ uniformly. As in Lemma 2, for a point in D_1, this allows us to estimate the kernel for $H^\epsilon_\beta(u + iv)$.

Lemma 7. *Suppose $(u + iv)$ is such that the corresponding point on the leaf L^ϵ_β is in D_1, then if $|y| < 2(\log(1/|\epsilon|))^\gamma$,*

$$\frac{(r)^\gamma \sin(\gamma\theta)}{((r)^\gamma \sin(\gamma\theta))^2 + (y - (r)^\gamma \cos(\gamma\theta))^2} \sim \frac{1}{(\log(1/|\epsilon|))^\gamma}\,.$$

On the other hand if $|y| \geq 2(\log(1/|\epsilon|))^\gamma$ then

$$\frac{(r)^\gamma \sin(\gamma\theta)}{((r)^\gamma \sin(\gamma\theta))^2 + (y - (r)^\gamma \cos(\gamma\theta))^2} \sim \frac{(\log(1/|\epsilon|))^\gamma}{y^2}\,.$$

Hence using Lemma 2 and Lemma 7 we get

Lemma 8. *We have the following estimate of H^ϵ_β for points in D_1:*

$$H^\epsilon_\beta \sim \frac{1}{(\log(1/|\epsilon|))^\gamma} \int_{|y|<2(\log(1/|\epsilon|))^\gamma} \tilde{H}_\beta(y)dy + \big(\log(1/|\epsilon|)\big)^\gamma \int_{|y|\geq 2(\log(1/|\epsilon|))^\gamma} \frac{\tilde{H}_\beta(y)}{y^2}dy\,. \tag{2.8}$$

Next, we fix α, β and plaques $L_{\alpha,n}, L^\epsilon_{\beta,m}$ and assume they intersect in D_1. By Lemma 6, there are conditions on m for this to happen, namely,

$$2m\pi < u' < 2(m+1)\pi$$

$$\text{and} \quad \frac{1-a}{b}\log\big(1/|\epsilon|\big) - C < u' < \frac{1-a}{b}\log\big(1/|\epsilon|\big) + C\,.$$

$$\text{So,} \quad \frac{1-a}{b}\log\big(1/|\epsilon|\big) - C - 2\pi < 2m\pi < \frac{1-a}{b}\log\big(1/|\epsilon|\big) + C\,.$$

We pick a plaque $L^\epsilon_{\beta,m}$ with an intersection point in D_1. Then this plaque is of the form $w = f(z) = f_\eta(z)$ where $f_\eta(\eta) = 0$ and f' is as in Lemma 5, i.e. close to $\lambda\frac{\beta'(0)}{\alpha'(0)}$. Next consider a plaque $L_{\alpha,n}$. Then $z = e^{i(u+(\log|\alpha|/b))-v}$ and $w = \alpha e^{i\lambda(\zeta+(\log|\alpha|)/b)}$. Hence $2n\pi < u < 2(n+1)\pi$ and $|w| = e^{-bu-av}$.

We estimate the location of the intersection points.

Case 1: $|z - \eta| < d|\eta|$, $0 < d \ll 1$. The constant d will be chosen small enough, in order to satisfy an inequality at the end of the proof of Lemma 9.

We estimate the parameter values (u, v) for $L_{\alpha,n}$.

Since $|\eta|(1-d) < |z| = e^{-v} < |\eta|(1+d)$, $\log(1/|\eta|) - 2d < v < \log(1/|\eta|) + 2d$. Note that also, for the point (z, w) to be on $L^\epsilon_{\beta,m}$ with $|z - \eta| < d|\eta|$ we must have that $|w| < 2|\lambda|\frac{|\beta'(0)|}{|\alpha'(0)|}d|\eta|$.

Lemma 9. *For (z, w) to be an intersection point between $L_{\alpha,n}$ and L^ϵ_β in D_1 with $|z - \eta| < d|\eta|$, we must have*

(i) $2n\pi < u < 2(n+1)\pi$;
(ii) $2n\pi > \frac{1-a}{b}\log(1/|\eta|) - C$;
(iii) $\log(1/|\eta|) - 2d < v < \log(1/|\eta|) + 2d$.

Moreover there is at most one such intersection point.

Proof. We have already proved (iii) and (i) is given. To prove (ii):

$$|w| = e^{-bu-av} < 2|\lambda|\frac{|\beta'(0)|}{|\alpha'(0)|}d|\eta|\,.$$

So,

$$bu - av < \log|\eta| + C\,.$$

Using the estimate on v we get $u > ((1-a)/b)\log(1/|\eta|) - C'$ where C' is an absolute constant.

To prove the last part, notice that the slope of L^ϵ_β is about λ while the slope of L_α is $\lambda w/z$ so is at most $|\lambda|(2|\lambda|\frac{|\beta'(0)|}{|\alpha'(0)|}d||\eta|)/(|\eta|(1-d)) \ll |\lambda|$ if we just make d small enough. □

Lemma 10. *We estimate the value of H_α at intersection points between $L_{\alpha,n}$ and L^ϵ_β in D_1 with $|z-\eta| < d|\eta|$. We have two cases:* (i) $\frac{1-a}{b}\log(1/|\eta|) - C < 2\pi n < C\log(1/|\eta|)$. *Then we have*

$$H_\alpha(u+iv) \sim \int_{|x|<2(\log(1/|\eta|))^\gamma} \frac{\tilde{H}_\alpha(x)}{(\log(1/|\eta|))^\gamma} + \int_{|x|>2(\log(1/|\eta|))^\gamma} \tilde{H}_\alpha(x)\frac{(\log(1/|\eta|))^\gamma}{x^2}\,.$$

In the next case, (ii) $2\pi n \geq C\log(1/|\eta|)$, *we then have* $U+iV \sim n^\gamma + in^{\gamma-1}\log\left(\frac{1}{|\eta|}\right)$ *and*

$$H_\alpha(u+iv) \sim \int_{|x-U|<n^{\gamma-1}\log(1/|\eta|)} \frac{\tilde{H}_\alpha(x)}{n^{\gamma-1}\log(1/|\eta|)}dx + \int_{|x-U|>n^{\gamma-1}\log(1/|\eta|)} \frac{\tilde{H}_\alpha(x)n^{\gamma-1}\log(1/|\eta|)}{(x-U)^2}dx\,.$$

Proof. Case (i): We use that $\sin(\gamma\theta)$ is bounded below by a strictly positive constant. Case (ii) is clear. □

Case 2: Our next step is to discuss intersection points of $L_{\alpha,n}$ and $L^\epsilon_{\beta,m}$ in D_1 for which $|z-\eta| > d|\eta|$. Note that $L^\epsilon_{\beta,m}$ intersects the w-axis close to $\left(0, -\lambda\frac{\beta'(0)}{\alpha'(0)}\eta\right)$ and the above argument applies as well to the region $\left|w + \lambda\frac{\beta'(0)}{\alpha'(0)}\eta\right| < d|\eta|$. Hence we only need to consider intersections of $L_{\alpha,n}$ and $L^\epsilon_{\beta,m}$ when $\left|w + \lambda\frac{\beta'(0)}{\alpha'(0)}\eta\right| > d|\eta|$ and also $|z-\eta| > d|\eta|$, call this set S'.

Note: This is the place in the argument where we will assume that $a \neq 1$.

Since we are excluding the points near where $L^\epsilon_{\beta,m}$ crosses the two axes, we have the following estimate on points in $L^\epsilon_{\beta,m}$: For some fixed constant $R > 1$ we have that

$$\tfrac{1}{R}|w| < |z| < R|w|$$

for points in S'.

Hence $\frac{1}{R}e^{-av-bu} < e^{-v} < Re^{-av-bu}$. So $bu - \log R < (1-a)v < bu + \log R$. Therefore $2nb\pi/(1-a) - C' < v < 2nb\pi/(1-a) + C'$. □

LEMMA 11 (Intersection lemma). *There is a constant $N > 1$ so that if we cover the rectangle $2n\pi < u < (2n+1)\pi$, $2nb\pi/(1-a) - C' < v < 2nb\pi/(1-a) + C'$ with N equal squares, then there are at most two intersection points in each square.*

Proof. We choose N so that, in each square, the slope of $L_{\alpha,n}$ is almost constant and will produce at most one intersection point. The exception is when the slope is close to $\lambda\frac{\beta'(0)}{\alpha'(0}$. Then there might be a tangency between $L_{\alpha,n}$ and L_β. Hence there might be two or more intersection points counted with multiplicity. We will show there are at most 2. Note that the slope S of $L_{\alpha,n}$ is given by the quotient $\lambda w/z$.

$$\begin{aligned} dw/dz &= \lambda w/z \\ &= \lambda\frac{\alpha e^{i\lambda(\zeta+(\log|\alpha|/b))}}{e^{i(u+(\log|\alpha|/b))-v}} \\ &= \frac{\lambda\alpha e^{((\log|\alpha|)/b)(-b+ia)}}{e^{i(\log|\alpha|)/b}}\frac{e^{i\lambda\zeta}}{e^{i\zeta}}. \end{aligned}$$

So, $S = Ce^{i(\lambda-1)\zeta}$ and $\frac{\partial S}{\partial\zeta} = i(\lambda-1)S \sim i(\lambda-1)\lambda\frac{\beta'(0)}{\alpha'(0)} \sim 1$.

This says that the slope of $L_{\alpha,n}$ near intersection points vary very rapidly, while we also see from Lemma 5 that the slope of $L^\epsilon_{\beta,m}$ varies slowly. This implies that near tangential intersection points there are at most two of them. □

We estimate the value of H_α at points p where $L_{\alpha,n}$ and $L^\epsilon_{\beta,m}$ intersect in D_1 away from the axes $\left(|z-\eta| > d|\eta|, \left|w + \lambda\frac{\beta'(0)}{\alpha'(0)}\eta\right| > d|\eta|\right)$.

LEMMA 12. *For the intersection point to be in D_1 we need $|n| > \frac{|1-a|\log(1/|\epsilon|)}{2\pi b} - C_1$. Then*

$$H_\alpha(p) \sim \int_{|x|<C_2|n|^\gamma}\frac{\tilde{H}_\alpha(x)dx}{|n|^\gamma} + \int_{|x|>C_2|n|^\gamma}\frac{\tilde{H}_\alpha(x)|n|^\gamma}{x^2}dx\,.$$

Proof. For the first estimate, recall that $|z| = e^{-v} < c|\epsilon|$ and that $2nb\pi/(1-a) - C' < v < 2nb\pi/(1-a) + C'$. For the integral estimate we see that $(u+iv)^\gamma = U + iV$ with $V \sim |n|^\gamma$ and $|U| <\sim |n|^\gamma$. Then the estimate is immediate from the Poisson kernel. □

We complete the estimate in Theorem 7 for D_1.

Theorem 8. *The contribution to the geometric wedge product of T and T_ϵ from intersection points in D_1 goes to zero when $\epsilon \to 0$.*

Proof. Let $I = I_\epsilon$ consist of all intersection points p in D_1. They are labeled $p = p_{\alpha,\beta,n,m,\ell}$ if they belong to the plaques $L_{\alpha,n}, L^\epsilon_{\beta,m}$ and ℓ lists them (with multiplicity) if there are more than one. By Lemma 6,

$$\frac{(1-a)\log(1/|\epsilon|)}{2\pi b} - C < m < \frac{(1-a)\log(1/|\epsilon|)}{2\pi b} + C$$

so in particular there are at most finitely many values of m and there is a uniform upper bound on the number of them. We can hence restrict to one fixed value of m. Next recall that from Lemma 8 we have the estimate (2.8) on the value of H^ϵ_β at each intersection point.

By Lemmas 9 and 11 there is at most a uniformly bounded number of intersection points with $L_{\alpha,n}$ and $L^{\epsilon}_{\beta,m}$ in D_1. Hence when we estimate the geometric wedge product we can factor out the contribution from β and we get, using (2.8), an upper bound of

$$\int \Big(\sum_p H^{\epsilon}_{\beta}\Big) d\mu(\beta) \lesssim \frac{1}{(\log(1/|\epsilon|))^{\gamma}} \int_{|y|<2(\log(1/|\epsilon|))^{\gamma}} \tilde{H}_{\beta}(y) dy d\mu(\beta) + \big(\log(1/|\epsilon|)\big)^{\gamma} \int_{|y|>2(\log(1/|\epsilon|))^{\gamma}} \frac{\tilde{H}_{\beta}(y)}{y^2} dy d\mu(\beta)\,.$$

We collect a few estimates that will be used repeatedly in the Lebesgue dominated convergence theorem.

LEMMA 13. *We have the following integral estimates.*

(I)
$$\frac{1}{(\log(1/|\epsilon|))^{\gamma}} \int_{|y|<2(\log(1/|\epsilon|))^{\gamma}} \tilde{H}_{\beta}(y) dy \sim \int_{|y|<2(\log(1/|\epsilon|))^{\gamma}} \tilde{H}_{\beta}(y) |y|^{1/\gamma-1} \frac{|y|}{(\log(1/|\epsilon|))^{\gamma}} \frac{1}{(|y|+1)^{1/\gamma}} dy$$

and

(II) *If* $U \sim n^{\gamma}$, *then*
$$\int_{|x-U|<n^{\gamma-1}\log(1/|\eta|)} \frac{\tilde{H}_{\alpha}(x)}{n^{\gamma-1}\log(1/|\eta|)} dx \sim \int_{|x-U|<n^{\gamma-1}\log(1/|\eta|)} \tilde{H}_{\alpha}(x)|x|^{1/\gamma-1} \frac{dx}{\log(1/|\eta|)}\,. \quad \square$$

We want to show that
$$\int \sum_p H^{\epsilon}_{\beta} d\mu(\beta) \to 0\,.$$

We use the a priori bound that we found and estimate (I) in the previous lemma. The Lebesgue dominated convergence theorem and Proposition 1 gives the result.

End of the proof of Theorem 8. After integrating with respect to μ and using (I) of Lemma 13 we can use the dominated convergence theorem. We estimate the value of H_{α} at one of the intersection points $p \in D_1$. From Lemma 2 we have
$$H_{\alpha}(p) = \frac{1}{\pi} \int \tilde{H}_{\alpha}(x) \frac{\rho^{\gamma}\sin(\gamma\theta)}{(\rho^{\gamma}\sin(\gamma\theta))^2 + (x-\rho^{\gamma}\cos(\gamma\theta))^2} dx\,.$$

Case (i): $|z-\eta| < d|\eta|$, $|n| < C\log(1/|\eta|)$. By Lemma 9 it follows that $V = \rho^{\gamma}\sin(\gamma\theta) \sim (\log(1/|\eta|))^{\gamma}$ and $|U| <\sim (\log(1/|\eta|))^{\gamma}$. So we get
$$H_{\alpha}(p) \sim \int_{|x|<C(\log(1/|\eta|))^{\gamma}} \frac{\tilde{H}_{\alpha}(x)dx}{(\log(1/|\eta|))^{\gamma}} + \int_{|x|>C(\log(1/|\eta|))^{\gamma}} \tilde{H}_{\alpha}(x) \frac{(\log(1/|\eta|))^{\gamma}}{x^2} dx\,.$$

Adding up we get
$$\sum_{|n|<\log(1/|\eta|)} h_{\alpha,n}(p_n) \sim \int_{|x|<C(\log(1/|\eta|))^{\gamma}} \tilde{H}_{\alpha}(x)|x|^{1/\gamma-1} \left(\frac{|x|}{(\log(1/|\eta|))^{\gamma}}\right)^{1-1/\gamma} dx + \int_{|x|>C(\log(1/|\eta|))^{\gamma}} \tilde{H}_{\alpha}(x)|x|^{1/\gamma-1} \left(\frac{(\log(1/|\eta|))^{\gamma}}{|x|}\right)^{1+1/\gamma} dx\,.$$

Integrating with respect to μ we get that $\sum_{|n|<\log(1/|\eta|)} h_{\alpha,n}(p_n) \to 0$ as $\epsilon \to 0$ since $|\eta| < \epsilon$. We use again the estimates in Lemma 13 and Proposition 1.

Case (ii): $|z-\eta| < d|\eta|$, $|n| > C\log(1/|\eta|)$. Then by Lemma 9, $n > 0$ and we have $U_n \sim n^\gamma$, $V \sim n^{\gamma-1}\log(1/|\eta|)$. From Lemma 10 we have

$$H_\alpha(p) \sim \int_{|x-U|<n^{\gamma-1}\log(1/|\eta|)} \frac{\tilde{H}_\alpha(x)}{\log(1/|\eta|)} x^{1/\gamma-1} dx + \int_{|x-U|>n^{\gamma-1}\log(1/|\eta|)} \tilde{H}_\alpha(x) \frac{n^{\gamma-1}\log(1/|\eta|)}{|x-U|^2} dx\,.$$

Therefore,

$$\begin{aligned}\sum_{n>C\log(1/|\eta|)} H_{\alpha,n}(p) &\sim \sum_{n>C\log(1/|\eta|)} \int_{|x-U_n|<n^{\gamma-1}\log(1/|\eta|)} \frac{\tilde{H}_\alpha(x)}{\log(1/|\eta|)} x^{1/\gamma-1} dx \\ &\quad + \sum_{n>C\log(1/|\eta|)} \int_{|x-U_n|>n^{\gamma-1}\log(1/|\eta|)} \tilde{H}_\alpha(x) \frac{n^{\gamma-1}\log(1/|\eta|)}{|x-U_n|^2} dx \\ &= \mathrm{I} + \mathrm{II}\,.\end{aligned}$$

We are going to estimate I and II separately. Note that for a given x, the number of integers n for which $U_n - n^{\gamma-1}\log(1/|\eta|) < x < U_n + n^{\gamma-1}\log(1/|\eta|)$ is bounded above by a multiple of $\log(1/|\eta|)$. It follows that $I <\sim \int_{(\log(1/|\eta|))^\gamma/C}^{\infty} \tilde{H}_\alpha(x) x^{1/\gamma-1} dx$. This contribution goes to zero as $|\epsilon| \to 0$ since $|\eta| < |\epsilon|$.

To study II we estimate U_n more precisely. We have $2n\pi < u_n < 2(n+1)\pi$ and $\log(1/|\eta|) - 2d < v_n < \log(1/|\eta|) + 2d$, and $(u_n + iv_n)^\gamma = u_n^\gamma(1 + iv_n/u_n)^\gamma = u_n^\gamma + \gamma u_n^{\gamma-1} iv_n + E_n$, with $|E_n| \lesssim u_n^\gamma (v_n/u_n)^2 \sim n^{\gamma-2}(\log(1/|\eta|))^2$.

Hence $|U_n - (2n\pi)^\gamma| \ll n^{\gamma-1}\log(1/|\eta|)$. We can hence replace U_n by $(2n\pi)^\gamma$ in II without changing the order of magnitude of the expression. We divide II into pieces II_A,II_B,II_C. In II_A and in II_C, x is such that $n > C\log(1/|\eta|)$.

In II_B, n has a range of the form $n > x^{1/\gamma} + r(x)\log(1/|\eta|)$, $r(x) \sim 1$ and in $C\log(1/|\eta|) < n < x^{1/\gamma} - s(x)\log(1/|\eta|)$, $s(x) \sim 1$. So

$$\mathrm{II} = \mathrm{II}_A + \mathrm{II}_B + \mathrm{II}_C\,.$$

For II_A we have

$$\begin{aligned}\mathrm{II}_A &= \int_{x=-\infty}^{C_1(\log(1/|\eta|))^\gamma} \sum_{n>C\log(1/|\eta|)} \tilde{H}_\alpha(x) \frac{n^{\gamma-1}\log(1/|\eta|)}{|x-n^\gamma|^2} dx \\ &\sim \int_{|x|<C_1(\log(1/|\eta|))^\gamma} \tilde{H}_\alpha(x) \frac{\log(1/|\eta|)}{[10\log(1/|\eta)|]^\gamma - x} dx \\ &\quad + \int_{x=-\infty}^{-C_1(\log(1/|\eta|))^\gamma} \tilde{H}_\alpha(x) \frac{\log(1/|\eta|)}{[10\log(1/|\eta)|]^\gamma - x} dx \\ &\sim \int_{|x|<C_1(\log(1/|\eta|))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1} \left(\frac{|x|}{[\log(1/|\eta|)]^\gamma}\right)^{1-1/\gamma} dx \\ &\quad + \int_{x=-\infty}^{-C_1(\log(1/|\eta|))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1} \left(\frac{(\log(1/|\eta|))^\gamma}{|x|}\right)^{1/\gamma} dx\,.\end{aligned}$$

For

$$\mathrm{II}_B \sim \int_{x=C_1(\log(1/|\eta|))^\gamma}^{\infty} \sum_{n>x^{1/\gamma}+r(x)\log(1/|\eta|)} \tilde{H}_\alpha(x)\frac{n^{\gamma-1}\log(1/|\eta|)}{|x-n^\gamma|^2}dx$$
$$\sim \int_{x=C_1(\log(1/|\eta|))^\gamma}^{\infty} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}dx\,,$$

and

$$\mathrm{II}_C \sim \int_{x=C_2(\log(1/|\eta|))^\gamma}^{\infty} \sum_{C\log(1/|\eta|)<n<x^{1/\gamma}-s(x)\log(1/|\eta|)} \tilde{H}_\alpha(x)\frac{n^{\gamma-1}\log(1/|\eta|)}{|x-n^\gamma|^2}dx$$
$$\mathrm{II}_C \sim \int_{x=C_2(\log(1/|\eta|))^\gamma}^{\infty} \tilde{H}_\alpha(x)x^{1/\gamma-1}dx\,.$$

Integrating with respect to μ we get

$$\int \mathrm{II}\,d\mu(\alpha) \sim \int_\alpha \mathrm{II}_A d\mu(\alpha) + \int_\alpha \mathrm{II}_B d\mu(\alpha) + \int_\alpha \mathrm{II}_C d\mu(\alpha)$$
$$\lesssim \int_\alpha \int_{|x|>(\log(1/|\eta|))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}dx d\mu(\alpha)$$
$$+ \int_\alpha \int_{|x|<C_1(\log(1/|\eta|))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\left(\frac{|x|}{(\log(1/|\eta|))^\gamma}\right)^{1-1/\gamma} dx d\mu(\alpha)\,,$$

which tends to 0 as $\eta \to 0$. (Recall that $|\eta| < \epsilon$.)

Case (iii): $|w+\lambda\eta| < d|\eta|$. This case is symmetric to cases (i) and (ii), so done.

Case (iv): $|z|, |w| < c|\epsilon|$; $|z-\eta|, |w+\lambda\eta| > d|\eta|$. We recall the estimate of $H_{\alpha,n}(p)$ at intersection points from Lemma 12. The contribution W to the geometric wedge product is

$$\int_\alpha \left[\sum_{|n|>[|1-a|\log(1/|\epsilon|)]/[2\pi b]-C} \int_{|x|<2|n|^\gamma} \frac{\tilde{H}_\alpha(x)dx}{|n|^\gamma} + \int_{|x|>2|n|^\gamma} \frac{\tilde{H}_\alpha(x)|n|^\gamma}{x^2}dx \right] d\mu(\alpha)\,.$$

We divide the first integral into two pieces, so $W = W_A + W_B + W_C$. We get

$$W_A \sim \int_\alpha \left[\int_{|x|<2|[|1-a|\log(1/|\epsilon|)]/[2\pi b]-C|^\gamma} \sum_{|n|>[|1-a|\log(1/|\epsilon|)]/[2\pi b]-C} \frac{\tilde{H}_\alpha(x)dx}{|n|^\gamma} \right] d\mu(\alpha)$$
$$\sim \int_\alpha \left[\int_{|x|<2|[|1-a|\log(1/|\epsilon|)]/[2\pi b]-C|^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\left(\frac{|x|}{(\log(1/|\epsilon|))^\gamma}\right)^{1-1/\gamma} dx \right] d\mu(\alpha)$$
$$\to 0 \quad \text{as } \epsilon \to 0\,.$$

For W_B replacing similarly the sum by an integral, we have

$$W_B \sim \int_\alpha \left[\int_{|x|>2|[|1-a|\log(1/|\epsilon|)]/[2\pi b]-C|^\gamma} \sum_{(|x|/2)^{1/\gamma}}^{\infty} \frac{\tilde{H}_\alpha(x)dx}{|n|^\gamma} \right] d\mu(\alpha)$$
$$W_B \sim \int_\alpha \left[\int_{|x|>2|[|1-a|\log(1/|\epsilon|)]/[2\pi b]-C|^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}dx \right] d\mu(\alpha)$$
$$\to 0\,,$$

again by Proposition 1. Finally, for W_C we get

$$W_C \sim \int_\alpha \left[\int_{|x|>2|\frac{|1-a|\log(1/|\epsilon|)}{2\pi b}-C|^\gamma} \sum_{|n|=[|1-a|\log(1/|\epsilon|)]/[2\pi b]-C}^{(|x|/2)^{1/\gamma}} \frac{\tilde{H}_\alpha(x)|n|^\gamma dx}{x^2} \right] d\mu(\alpha)$$

$$\sim \int_\alpha \left[\int_{|x|>2|[|1-a|\log(1/|\epsilon|)]/[2\pi b]-C|^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1} dx \right] d\mu(\alpha)\,,$$

and hence $W_C \to 0$.

Now we have finished the part of the proof of Theorem 8 where we consider intersection points in $D_1 = \{|z|, |w| < c|\epsilon|\}$.

4 Proof of Theorem 7 for Intersection Points in $D_2 \subset \Delta^2(0, C|\epsilon|)$ close to the separatrices

We split D_2 into regions A' and B where A' denotes points close to the separatrices and B denotes the rest. Then A' has 2 pieces. It suffices to consider one, $A = \{(z,w); c|\epsilon| < |z| < C|\epsilon|, |w| < r|\epsilon|\}$ where $0 < r < c$ depends on the choice of C.

We consider intersection points of $L_{\alpha,n}$ and $L^\epsilon_{\beta,m}$ in A. We parametrize L_α with $(u+iv)$ and L^ϵ_β with $u'+iv'$. In A we have for $L_{\alpha,n}$: $\log(1/|\epsilon|)-C < v < \log(1/|\epsilon)+C$ and $|w| = e^{-bu-av} < r|\epsilon|$. So $u > \frac{1-a}{b}\log(1/|\epsilon|) - C$ and $n > \frac{1-a}{2\pi b}\log(1/|\epsilon|) - C$.

For $L^\epsilon_{\beta,m}$ we have in A, since $|z'| < C|\epsilon|$ that $v' > \log(1/|\epsilon|) - C$. Therefore,

$$\frac{1}{b}\log\left(\frac{1}{|\epsilon|}\right) - \frac{2c}{b} - \frac{av'}{b} < u' < \frac{1}{b}\log\left(\frac{1}{|\epsilon|}\right) - \frac{av'}{b} + \frac{2c}{b}\,.$$

The m's are estimated later and they depend on which case we are in, $a = 0$ or not.

LEMMA 14. *If $a \neq 0$, there is an integer N so that for small r, there are at most N intersection points between any pair $L_{\alpha,n}$ and $L^\epsilon_{\beta,m}$.*

Proof. This follows from considering the slopes of the plaques, given by the forms ω, ω_ϵ. Namely the slope of the $L_{\alpha,n}$ is very small and the slope of $L^\epsilon_{\beta,m}$ has close to constant larger modulus and close to constant argument on each of N small squares where there might be an intersection. □

Next we estimate $h_{\alpha,n}$ at an intersection point.

Case (i): $n < \log(1/|\epsilon|)$: In U, V coordinates we have $V \sim (\log(1/|\epsilon|))^\gamma$, $|U| \lesssim (\log(1/|\epsilon|))^\gamma$. Using the expression as a Poisson integral we get

$$h_{\alpha,n}(p) \sim \int_{|x|<C(\log(1/|\epsilon|))^\gamma} H_\alpha(x)|x|^{1/\gamma-1} \frac{|x|}{(\log(1/|\epsilon|))^\gamma} |x|^{-1/\gamma} dx$$
$$+ \int_{|x|>C(\log(1/|\epsilon|))^\gamma} H_\alpha(x)|x|^{1/\gamma-1} \frac{(\log(1/|\epsilon|))^\gamma}{|x|} |x|^{-1/\gamma} dx\,.$$

Case (ii): $n > \log(1/|\epsilon|)$. Then $U \sim n^\gamma$, $V \sim n^{\gamma-1}\log(1/|\epsilon|)$. Hence

$$h_{\alpha,n}(p) \sim \int H_\alpha(x) \frac{n^{\gamma-1}\log(1/|\epsilon|)}{(n^{\gamma-1}\log(1/|\epsilon|))^2 + |x-n^\gamma|^2} dx\,.$$

We observe that this integral has already been estimated above. Namely see Case (ii), integrals I + II.

So we get

$$\sum_{n>10\log(1/|\epsilon|)} h_{\alpha,n}(p) \lesssim \int_{|x|>(\log(1/|\epsilon|)^\gamma} H_\alpha(x)|x|^{1/\gamma-1}dx + \int_{|x|<C(\log(1/|\epsilon|))^\gamma} H_\alpha(x)|x|^{1/\gamma-1}\left(\frac{|x|}{\log(1/|\epsilon|)}\right)^\gamma dx\,.$$

We estimate next $h^\epsilon_{\beta,m}(p)$. From the above estimates for u', v' we see that $|u'| <\sim v'$ and hence $V' \sim (v')^\gamma$, $|U'| \lesssim (v')^\gamma$. We then have

$$h^\epsilon_{\beta,m}(p) \sim \int_{|y|<C(v')^\gamma} H_\beta(y)|y|^{1/\gamma-1}\left(\frac{|y|}{(v')^\gamma}\right)^{1-1/\gamma}\frac{1}{v'}dy + \int_{|y|>C(v')^\gamma} H_\beta(y)|y|^{1/\gamma-1}\left(\frac{(v')^\gamma}{|y|}\right)^{1+1/\gamma}\frac{1}{v'}dy\,.$$

Note that for $a \neq 0$, we have that

$$\log\big(1/|\epsilon|\big)/a - bu'/a - 2c/|a| < v' < \log\big(1/|\epsilon|\big)/a - bu'/a + 2c/|b|$$
$$\text{and}\qquad \log\big(1/|\epsilon|\big)/a - 2m\pi b/a - C < v' < \log\big(1/|\epsilon|\big)/a - 2m\pi b/a + C\,.$$

So $v' > \log(1/|\epsilon|)$ and $m/a < \frac{1}{2\pi b}\log(1/|\epsilon|)(1/a-1) + C$.

Define

$$\Sigma := \sum_{m/a<\frac{1}{2\pi b}\log(1/|\epsilon|)(1/a-1)+C} h^\epsilon_{\beta,m}\,.$$

Then using the above estimates,

$$\Sigma \lesssim \sum_m \int_{|y|<C(\log(1/|\epsilon|)/a-b2m\pi/a)^\gamma} H_\beta(y)|y|^{1/\gamma-1} * \left(\frac{|y|}{(\log(1/|\epsilon|)/a-b2m\pi/a)^\gamma}\right)^{1-1/\gamma} * \frac{1}{|\log(1/|\epsilon|)/a-b2m\pi/a|}dy$$
$$+ \sum_m \int_{|y|>C(\log(1/|\epsilon|)/a-b2m\pi/a)^\gamma} H_\beta(y)|y|^{1/\gamma-1} * \left(\frac{(\log(1/|\epsilon|)/a-b2m\pi/a)^\gamma}{|y|}\right)^{1+1/\gamma} * \frac{1}{\log(1/|\epsilon|)/a-b2m\pi/a}dy = \mathrm{I}+\mathrm{II}\,.$$

We study I and II separately. We split I into two parts:

$$\mathrm{I} = \mathrm{I}_A + \mathrm{I}_B\,.$$

For I_A we have

$$\mathrm{I}_A = \int_{|y|<C(\log(1/|\epsilon|))^\gamma} \sum_{m/a<\frac{1}{2\pi b}\log(1/|\epsilon|)(1/a-1)+C} H_\beta(y)|y|^{1/\gamma-1} * \left(\frac{|y|}{(\log(1/|\epsilon|)/a-b2m\pi/a)^\gamma}\right)^{1-1/\gamma} * \frac{1}{|\log(1/|\epsilon|)/a-b2m\pi/a|}dy$$
$$\sim \int_{|y|<C(\log(1/|\epsilon|))^\gamma} H_\beta(y)|y|^{1/\gamma-1}\left(\frac{|y|}{(\log(1/|\epsilon|))^\gamma}\right)^{1-1/\gamma}dy\,.$$

We estimate

$$\mathrm{I}_B = \int_{|y|=C(\log(1/|\epsilon|))^\gamma}^{\infty} \sum_{m/a<\frac{\log(1/|\epsilon|)}{2\pi ab}-(|y|/C)^{1/\gamma}} H_\beta(y)|y|^{1/\gamma-1} * \left(\frac{|y|}{(\log(1/|\epsilon|)/a-b2m\pi/a)^\gamma}\right)^{1-1/\gamma} * \frac{1}{|\log(1/|\epsilon|)/a-b2m\pi/a|}dy$$

$$\sim \int_{|y|=C(\log(1/|\epsilon|))^\gamma}^{\infty} H_\beta(y)|y|^{1/\gamma-1}dy\,.$$

For II we have

$$\mathrm{II} \sim \sum_{\frac{1}{2\pi b}\log(1/|\epsilon|)(1/a-1)>m/a>\frac{\log(1/|\epsilon|)}{2\pi ab}-(|y|/C)^{1/\gamma}} \int_{|y|=C(\log(1/|\epsilon|))^\gamma}^{\infty} H_\beta(y)|y|^{1/\gamma-1} * \left(\frac{(\log(1/|\epsilon|)/a-b2m\pi/a)^\gamma}{|y|}\right)^{1+1/\gamma} * \frac{1}{\log(1/|\epsilon|)/a-b2m\pi/a}dy$$

$$\lesssim \int_{|y|=C(\log(1/|\epsilon|))^\gamma}^{\infty} H_\beta(y)|y|^{1/\gamma-1}dy\,.$$

With these estimates it follows that Theorem 7 is proved for the region A close to the separatrices, in the ball D_2 provided that $a \neq 0$.

For brevity we skip the case $a = 0$ which can be handled adapting the estimates.

We next consider the set B of points in $\Delta^2(0, C|\epsilon|)$ defined above as consisting of points which are at distance at least $r|\epsilon|$ from all separatrices.

5 Proof of Theorem 7 for Points in B, i.e. Points in D_2 which are at Distance at Least $r|\epsilon|$ from the Separatrices

We estimate H_α on $L_{\alpha,n} \cap B$. We can assume $a \neq 1$, otherwise flip the axes. So $r|\epsilon| < |z| < C|\epsilon|$, hence $\log(1/|\epsilon|) - C' < v < \log(1/|\epsilon|) + C'$.

Similarly it follows that $r|\epsilon| < |w| < C|\epsilon|$, therefore $\frac{1-a}{b}\log(1/|\epsilon|) - C < u < \frac{1-a}{b}\log(1/|\epsilon|) + C$.

Using these estimates on (u,v) and similarly for (u',v'), Lemma 11 shows that there is an integer N independent of ϵ so that if we take any two plaques of two leaves $L_\alpha, L^\epsilon_\beta$, then they intersect in B in at most N points. In U,V coordinates, $(u+iv)^\gamma = U+iV$, hence $V \sim (\log(1/|\epsilon|)^\gamma$ and $|U| <\sim (\log(1/|\epsilon|))^\gamma$.

This gives

$$h_{\alpha,n} \sim \int H_\alpha(x)\frac{(\log(1/|\epsilon|))^\gamma}{(\log(1/|\epsilon|))^{2\gamma}+(x-U)^2}dx$$

$$\sim \int_{|x|<C(\log(1/|\epsilon|))^\gamma} H_\alpha(x)\big(|x|+1\big)^{1/\gamma-1}\frac{|x|+1}{(\log(1/|\epsilon|))^\gamma}\big(|x|+1\big)^{-1/\gamma}dx$$

$$+ \int_{|x|>(\log(1/|\epsilon|)^\gamma} H_\alpha(x)\big(|x|+1\big)^{1/\gamma-1}\frac{(\log(1/|\epsilon|))^\gamma}{|x|+1}\big(|x|+1\big)^{-1/\gamma}dx\,.$$

It follows from these estimates applied to H_β as well that Theorem 7 is valid for intersection points in B.

6 Theorem 7 for $D_3 = \Delta^2(0,\delta) \setminus \Delta^2(0, C|\epsilon|)$

There are 3 regions to consider:

$$\begin{aligned}
&D_3 = R_1 \cup R_2 \cup R_3\,,\\
&R_1 = \big\{C|\epsilon| < |z| < \delta\,,\ C|\epsilon| < |w| < \delta\big\}\,,\\
&R_2 = \big\{C|\epsilon| < |z| < \delta\,,\ |w| < C|\epsilon|\big\}\,,\\
&R_3 = \big\{|z| < C|\epsilon|\,,\ C|\epsilon| < |w| < \delta\big\}\,.
\end{aligned}$$

Note that since we have assumed $a \neq 1$, the cases of R_2 and R_3 are not completely symmetric. We will leave it to the reader to verify that the estimates we do later for R_2 nevertheless hold for R_3.

7 Theorem 7 for R_1, the Diagonal Part of D_3

We first outline our approach. Fix parameters α, β and corresponding plaques $L_{\alpha,n}, L^{\epsilon}_{\beta,m}$. Next we divide R_1 into dyadic components, rings, $\{R(p)\}$ in the z-direction, $e^{-p-1} < |z| < e^{-p}$, $C|\epsilon| < |w| < \delta$. Then we estimate h_α and h_β on $L_{\alpha,n} \cap R(p)$ and $L^{\epsilon}_{\beta,m} \cap R(p)$ respectively. Next, for fixed α, β, n, m we estimate the values of p where the leaves $L_{\alpha,n}, L^{\epsilon}_{\beta,m}$ might intersect, and the number of intersection points for each such p. Putting this information together we can estimate the contribution from R_1 to the geometric wedge product.

Pick a plaque $L_{\alpha,n}$ and a point (z,w) in $L_{\alpha,n} \cap R(p)$ parametrized by (u,v). Then $e^{-p-1} < |z| = e^{-v} < e^{-p}$, so $\log(1/\delta) < v < \log(1/|\epsilon|) - C$ and $\log(1/\delta) < p < \log(1/|\epsilon|) - C$, so $2n\pi < u < 2(n+1)\pi$.

For w we have $C|\epsilon| < |w| < \delta$. So $\frac{\log(1/\delta)}{b} - \frac{av}{b} < u < \frac{\log(1/|\epsilon|) - \log C}{b} - \frac{av}{b}$. We divide into cases depending on whether $a \neq 0$ or $a = 0$.

First, assume $a \neq 0$. We choose a constant $0 < s < 1$ so that $\frac{1}{2} < 1 + \frac{2sb\pi}{a} < \frac{3}{2}$.

Case (i): $a \neq 0$, $n < sp$, then $(u+iv)^\gamma = U + iV \sim U + ip^\gamma$, $|U| <\sim p^\gamma$. So we have

$$H_{\alpha,n} \sim \int_{|x|<Cp^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\left(\frac{|x|}{p^\gamma}\right)^{1-1/\gamma}\frac{1}{p}dx + \int_{|x|>Cp^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\left(\frac{p^\gamma}{|x|}\right)^{1+1/\gamma}\frac{1}{p}dx\,.$$

Case (ii): $a \neq 0$, $n > sp$, so $(u+iv)^\gamma = U + iV \sim n^\gamma + ipn^{\gamma-1}$.
Then

$$\begin{aligned}
H_{\alpha,n} \sim &\int_{|x-n^\gamma|\le pn^{\gamma-1}} \tilde{H}_\alpha(x)\frac{1}{pn^{\gamma-1}}dx + \int_{n^\gamma/2>|x-n^\gamma|>pn^{\gamma-1}} \tilde{H}_\alpha(x)\frac{pn^{\gamma-1}}{|x-n^\gamma|^2}dx\\
&+ \int_{n^\gamma/2<|x-n^\gamma|<2n^\gamma} \tilde{H}_\alpha(x)\frac{pn^{\gamma-1}}{n^{2\gamma}}dx + \int_{|x-n^\gamma|>2n^\gamma} \tilde{H}_\alpha(x)\frac{pn^{\gamma-1}}{x^2}dx\\
&= \mathrm{I} + \mathrm{II} + \mathrm{III} + \mathrm{IV}
\end{aligned}$$

We will leave the case $a = 0$ to the reader.

Our next step is to locate for which $R(p)$ there is an intersection between $L_{\alpha,n}$ and $L^\epsilon_{\beta,m}$.

Fix $L_{\alpha,n}$ and $L^\epsilon_{\beta,m}$ and assume $(z,w) \in L_{\alpha,n} \cap L^\epsilon_{\beta,m}$. We can write

$$z = e^{i(\zeta + (\log|\alpha|)/b}\,,$$
$$\zeta = u + iv\,,$$
$$2n\pi < u < 2(n+1)\pi\,,$$
$$|z| = e^{-v}.$$

Also $(z,w) = \Phi_\epsilon(z',w')$, $(z',w') \in L_{\beta,m}$. We have $z' = e^{i(\zeta' + (\log|\alpha|)/b}$, $\zeta' = u' + iv'$. Hence $2m\pi < u' < 2(m+1)\pi$, $|z'| = e^{-v'}$.

So

$$z = \alpha(\epsilon) + e^{i(\zeta' + (\log|\beta|)/b)} + \epsilon\mathcal{O}(z',w')\,,$$
$$w = \beta(\epsilon) + \beta e^{i\lambda(\zeta' + (\log|\beta|)/b)} + \epsilon\mathcal{O}(z',w')\,.$$

Our goal is to locate for which $R(p)$ the point (z,w) can belong to. So we need to find p so that $e^{-p-1} < |z| = e^{-v} < e^{-p}$, i.e. we need to get a good estimate for v in terms of α, β, n, m.

There are 4 unknowns, u, v, u', v'. However, $u \sim 2n\pi$, $u' \sim 2m\pi$, so we only have v, v' left. Also we have two equations for the z and w coordinates respectively. (In fact, since these are complex equations, we have 4 real equations for the two real unknowns v, v'.)

Before we proceed we show at first that for there to be an intersection, we actually must require that n and m are very close.

Lemma 15. *If $L_{\alpha,n}$ and $L^\epsilon_{\beta,m}$ intersect in R_1, it follows that $|m - n| \leq 1$.*

Proof. Recall that

$$\Phi_\epsilon(z,w) = \big(\alpha(\epsilon), \beta(\epsilon)\big) + (z,w) + \epsilon\mathcal{O}(z,w)\,.$$

If δ is chosen small enough, this implies that $|\epsilon\mathcal{O}(z,w)| \leq \sigma|\epsilon|$ for any given $0 < \sigma \ll 1$.

We pick two plaques, $L_{\alpha,n}, L^\epsilon_{\beta,m}$ and consider intersection points in R_1. Let $S > 0$ be such that $|\epsilon|/S < |\alpha(\epsilon)| - \sigma|\epsilon|$, $|\beta(\epsilon)| - \sigma|\epsilon| < |\alpha(\epsilon)| + \sigma|\epsilon|$, $|\beta(\epsilon)| + \sigma|\epsilon| < S$. Note that if we increase the constant C used in the definition of D_4, we can still use the same S. When the point is in $L_{\alpha,n}$ we have $|z| = \big|e^{i(\zeta + (\log|\alpha|)/b}\big| = e^{-v}$. So $\log(1/|\delta|) < v < \log(1/|\epsilon|) - C$, and $|w| = \big|\alpha e^{i\lambda(\zeta + (\log|\alpha|)/b)}\big| = e^{-bu - av}$.

If it is also in $L_{\beta,m}$, then $|z'| = \big|e^{i(\zeta' + (\log|\beta|)/b)}\big| = e^{-v'}$, hence $\log(1/|\delta|) < v' < \log(1/|\epsilon|) - C$. Also $|w'| = \big|\beta e^{i\lambda(\zeta' + (\log|\beta|)/b)}\big| = e^{-bu' - av'}$.

Since $L^\epsilon_{\beta,n} = \Phi_\epsilon(L_{\beta,m})$, the image point can be written

$$Z = \alpha(\epsilon) + e^{i(\zeta' + (\log|\beta|)/b)} + \epsilon\mathcal{O}(z',w')\,,$$
$$W = \beta(\epsilon) + \beta e^{i\lambda(\zeta' + (\log|\beta|)/b)} + \epsilon\mathcal{O}(z',w')\,.$$

Consider an intersection point in R_1 and set $\zeta' = \zeta + c + id$. Then

$$z = Z\,,$$

$$e^{-v-d} - S|\epsilon| < e^{-v} < e^{-v-d} + S|\epsilon|\,,$$
$$e^{-d} - Se^{v}|\epsilon| < 1 < e^{-d} + Se^{v}|\epsilon|\,.$$

So $Se^v|\epsilon| < S(1/(C|\epsilon|)|\epsilon| = S/C \ll 1$, and $|d| < 2Se^v|\epsilon| < 2S/C$.

For the other coordinate,

$$w = W\,,$$
$$e^{-bu-bc-av-ad} - S|\epsilon| < e^{-bu-av} < e^{-bu-bc-av-ad} + S|\epsilon|\,,$$

hence $Se^{bu+av}|\epsilon| < S/C \ll 1$. We then get easily $|bc| < 2Se^{bu+av}|\epsilon| + |a|2Se^v|\epsilon|$.

Also, $|c+id| < \frac{2S}{C}\big(1+\frac{1+|a|}{|b|}\big) \ll 1$. □

It is also convenient to show that α and β must be very close if there is an intersection. We estimate first the modulus and next the angle and finally we combine them.

Lemma 16. *Suppose $L_{\alpha,n}$ intersects $L^{\epsilon}_{\beta,m}$ in R_1. Then*

$$\big|\log(|\beta|/|\alpha|)\big| \le 2S|\epsilon|\big[e^v\,(b+|a|) + e^{bu+av}\big]\,.$$

Proof. We have $z = Z$, so $e^{i(\zeta+(\log|\alpha|)/b)} = \alpha(\epsilon) + e^{i(\zeta+c+id+(\log|\beta|)/b)} + \epsilon\mathcal{O}(z',w')$. Hence, $e^{i(\zeta+(\log|\alpha|)/b)}\big[1 - e^{ic-d+i(\log(|\beta|/|\alpha|)/b)}\big] = \alpha(\epsilon) + \epsilon\mathcal{O}(z',w')$. Taking the modulus, $\big|1 - e^{ic-d+i(\log|\beta|/|\alpha|)/b)}\big| \le Se^v|\epsilon| \ll 1$. This gives $|\log(|\beta|/|\alpha|)/b| \le 2Se^v|\epsilon| + 2Se^{bu+av}|\epsilon|/b + 2S(|a|/b)e^v|\epsilon|$. The lemma follows. □

We remark that the lemma as stated is slightly inaccurate. We only can conclude the estimate modulo 2π. However, the parameters $e^{-2\pi b} \le |\alpha|, |\beta| < 1$ so this problem arises when say $|\alpha|$ is close to 1 and $|\beta|$ is close to $e^{-2\pi b}$. We ignore this technicality which just means that $|\alpha|$ and $|\beta|$ get close after we follow the leaf L_α once around 0 counterclockwise. We show that $|\theta|$ is small.

Lemma 17. *Write $\beta/\alpha = |\beta/\alpha|e^{i\theta}$. If there are intersection points in R_1, θ is close to 0 mod 2π. More precisely,*

$$|\theta| \le 2Se^{bu+av}|\epsilon|\big[|a|/b + |a|/b + 1\big] + 2S|\epsilon|e^v\big[|a|^2/b + b + (|a| + |a|^2/b)\big]\,.$$

Proof. We again use the parametrization, $w = W$, i.e. $\alpha e^{i\lambda(\zeta+(\log|\alpha|/b))} = \beta(\epsilon) + \beta e^{i\lambda(\zeta+c+id+(\log|\beta|/b))} + \epsilon\mathcal{O}(z',w')$.

So $\beta(\epsilon) + \epsilon\mathcal{O}(z',w') = \alpha e^{i\lambda(\zeta+(\log|\alpha|/b))}\big[1 - \frac{\beta}{\alpha}e^{i\lambda(c+id+(\log|\beta|/b))}\big]$, hence $\big|1 - \frac{\beta}{\alpha}e^{i\lambda(c+id+(\log|\beta|/b))}\big| \le Se^{bu+av}|\epsilon|$.

Therefore, $Se^{bu+av}|\epsilon| \ge \big|1 - \frac{\beta}{\alpha}e^{[-bc-ad-(\log|\alpha|/b)]+i[ac-bd+a(\log(|\beta|/|\alpha|))/b]}\big|$, then $1 \gg Se^{bu+av}|\epsilon| \ge \big|1 - e^{[-bc-ad]+i[\theta+ac-bd+a(\log(|\beta|/|\alpha|))/b]}\big|$ and $2Se^{bu+av}|\epsilon| \ge |\theta + ac - bd + a(\log(|\beta|/|\alpha|))/b|$.

Therefore,

$$\begin{aligned}|\theta| &\le |ac| + |bd| + |a|\big|\log(|\beta|/|\alpha|)\big|/b + 2Se^{bu+av}|\epsilon| \\ &\le Se^{bu+av}|\epsilon|\big[2|a|/b + 2|a|/b + 2\big] \\ &\qquad + S|\epsilon|e^v\big[2|a|^2/b + 2b + 2(|a| + |a|^2/b)\big]\,.\end{aligned}$$

This gives the estimate. □

Lemma 18. *Suppose that $L_{\alpha,n} \cap L^{\epsilon}_{\beta,m} \cap R_1 \neq \emptyset$. Then,*

$$-\frac{1}{i\lambda}\log\left(\frac{\beta}{\alpha}\right) = ie^{-i\zeta-i(\log|\alpha|)/b}\big[\alpha(\epsilon)+\epsilon\mathcal{O}\big] + \frac{1}{i\lambda}e^{-i\lambda\zeta}\frac{e^{-i\lambda(\log|\alpha|)/b)}}{\alpha}\big[\beta(\epsilon)+\epsilon\mathcal{O}\big] + \mathcal{O}(\epsilon e^{-i\zeta})^2 + \mathcal{O}(e^{-i\lambda\zeta}\epsilon)^2.$$

Proof. Next we locate more precisely the intersections of $L_{\alpha,n}$ and $L^{\epsilon}_{\beta,m}$ in R_1. Let $z = Z$.

Then $e^{i\zeta+i(\log|\alpha|)/b} = \alpha(\epsilon) + e^{i\zeta'+i(\log|\beta|)/b} + \epsilon\mathcal{O}(z',w')$.

We define Δ by $\zeta' = \zeta + \Delta$. Then

$$e^{i\zeta+i(\log|\alpha|)/b} - e^{i\zeta+i\Delta+i(\log|\beta|)/b} = \alpha(\epsilon)+\epsilon\mathcal{O}\,,$$
$$e^{i\zeta+i(\log|\alpha|)/b}\big[1-e^{i\Delta+i(\log(|\beta|/|\alpha|)/b}\big] = \alpha(\epsilon)+\epsilon\mathcal{O}\,,$$

hence

$$1-e^{i\Delta+i(\log(|\beta|/|\alpha|)/b} = e^{-i\zeta-i(\log|\alpha|)/b}\big[\alpha(\epsilon)+\epsilon\mathcal{O}\big]\,.$$

This gives, since Δ is close to zero,

$$\Delta + \big(\log(|\beta|/|\alpha|)\big)/b = ie^{-i\zeta-i(\log|\alpha|)/b}\big[\alpha(\epsilon)+\epsilon\mathcal{O}\big] + \mathcal{O}(\epsilon e^{-i\zeta})^2.$$

Using $w = W$, we have

$$\begin{aligned} \alpha e^{i\lambda(\zeta+(\log|\alpha|)/b)} &= \beta(\epsilon) + \beta e^{i\lambda(\zeta+\Delta+(\log|\beta|)/b)} + \epsilon\mathcal{O} \\ e^{i\lambda\zeta}\big[\alpha e^{i\lambda(\log|\alpha|)/b\big)} - \beta e^{i\lambda(\Delta+(\log|\beta|)/b)}\big] &= \beta(\epsilon)+\epsilon\mathcal{O} \\ &= e^{i\lambda\zeta}e^{i\lambda(\log|\alpha|)/b)} \\ &\quad * \big[\alpha - \beta e^{i\lambda(ie^{-i\zeta-i(\log|\alpha|)/b}[\alpha(\epsilon)+\epsilon\mathcal{O}])}\big]\,. \end{aligned}$$

So

$$1-\frac{\beta}{\alpha}e^{i\lambda(\Delta+(\log|\beta|/|\alpha|)/b)} = e^{-i\lambda\zeta}\frac{e^{-i\lambda(\log|\alpha|)/b)}}{\alpha}\big[\beta(\epsilon)+\epsilon\mathcal{O}\big]$$
$$-\log\left(\frac{\beta}{\alpha}\right) + i\lambda\big(\Delta+(\log|\beta|/|\alpha|)/b\big) \sim e^{-i\lambda\zeta}\frac{e^{-i\lambda(\log|\alpha|)/b)}}{\alpha}\big[\beta(\epsilon)+\epsilon\mathcal{O}\big]\,.$$

We get for a suitable branch of log,

$$\Delta + \log\big(|\beta|/|\alpha|\big)/b - \frac{1}{i\lambda}\log\left(\frac{\beta}{\alpha}\right) = \frac{1}{i\lambda}e^{-i\lambda\zeta}\frac{e^{-i\lambda(\log|\alpha|)/b)}}{\alpha}\big[\beta(\epsilon)+\epsilon\mathcal{O}\big] + \mathcal{O}(e^{-i\lambda\zeta}\epsilon)^2.$$

Adding the two expressions with Δ, using Lemma 16 and that Δ is close to zero gives the lemma. □

To continue the search for intersection points of $L_{\alpha,n}, L^{\epsilon}_{\beta,m}$ in R_1, we divide R_1 into 3 pieces. We let $C_1 > 1$ be a large constant.

$$R_{1A} = \big\{C|\epsilon| < |z|\,,\ |w| < \delta\,,\ C_1|w| \le |z|\big\}\,,$$
$$R_{1B} = \big\{C|\epsilon| < |z|\,,\ |w| < \delta\,,\ C_1|z| \le |w|\big\}\,,$$
$$R_{1C} = \big\{C|\epsilon| < |z|\,,\ |w| < \delta\,,\ |z| \le C_1|w| \le C_1^2|z|\big\}\,.$$

Here the constant C_1 is chosen to work in the slope estimates before Lemma 19.

Observe that R_{1A} and R_{1B} are similar. We will leave it up to the reader to verify the estimates for R_{1B}.

8 Theorem 7 for R_{1A}, the Part of R_1 Close to the z-Axis

We will assume that $a \neq 0$ and leave the verification of the case $a = 0$ to the reader. If $|w| \ll |z|$, then the second term in the expression for $\log(\beta/\alpha)$ in Lemma 18 on the right dominates and we get $e^{av+bu}|\epsilon| \sim |(\beta/\alpha) - 1|$, hence $2n\pi < u < 2(n+1)\pi$ and $av \sim \log|(\beta/\alpha) - 1| + \log(1/|\epsilon|) - 2nb\pi$.

So $\left|v - \frac{\log|(\beta/\alpha)-1|+\log(1/|\epsilon|)-2nb\pi}{a}\right| < C$ and $C|\epsilon| < e^{-v} < \delta$, $\log 1/\delta < v < \log 1/|\epsilon| - C$, $p < v < p+1$, see the beginning of section 7.

Lemma 19. *For intersection points in R_{1A}, There is a constant C' such that*

$$\frac{C'|\epsilon|}{\delta} < |\beta - \alpha| < \frac{1}{C'}\,.$$

Proof. Since $e^{av+bu}|\epsilon| \sim \left|\frac{\beta}{\alpha} - 1\right| \sim |\beta - \alpha|$ and $e^{av+bu} = \frac{1}{|w|}$ we have $|\beta - \alpha| \sim \frac{|\epsilon|}{|w|}$. But $C|\epsilon| < |w| < |z|/C < \delta/C$. The lemma follows. □

With $R(p)$ as in the beginning of section 7 we get

Lemma 20. *Suppose that $L_{\alpha,n}$ intersects $L^{\epsilon}_{\beta,m}$ in R_{1A}. Then the intersection points must be in $R(p)$ for some p, such that*

$$\left|p - \frac{\log|(\beta/\alpha) - 1| + \log(1/|\epsilon|) - 2nb\pi}{a}\right| < C\,.$$

For the plaque to enter R_1 we further need n to satisfy

$$\log|(\beta/\alpha) - 1| + \log(1/|\epsilon|) - 2nb\pi \in I$$

where I is the interval with endpoints $a\log 1/\delta, a\log(1/|\epsilon|) - aC$

Our next step is to verify that there is a uniform bound on the number of intersection points of $L_{\alpha,n}, L^{\epsilon}_{\beta,m}$ in R_{1A}.

In order to study the number of intersections between plaques, we compare their slopes.

Suppose $(z,w) = (Z,W) := \Phi_\epsilon(z',w')$ is an intersection point of $L_{\alpha,n}$ and $L^{\epsilon}_{\beta,m}$ in R_1. The slope S_1 of $L_{\alpha,n}$ is $\lambda w/z$. The slope of the perturbed leaf is S_2. We choose the constant C_1 used in the definition of R_{1A}, R_{1B}, R_{1C} in the following estimates.

We have

$$\Phi'_\epsilon(z',w')(z',\lambda w') = \big(z' + \epsilon\mathcal{O}(z',w'), \lambda w' + \epsilon\mathcal{O}(z',w')\big)\,.$$

The slope

$$S_2 = \frac{\lambda w' + \epsilon\mathcal{O}(z',w')}{z' + \epsilon\mathcal{O}(z',w')} = \frac{\lambda W - \lambda\beta(\epsilon) + \epsilon\mathcal{O}(Z,W)}{Z - \alpha(\epsilon) + \epsilon\mathcal{O}(Z,W)}\,.$$

So

$$S_2 = \frac{\lambda w - \lambda\beta(\epsilon) + \epsilon\mathcal{O}(z,w)}{z - \alpha(\epsilon) + \epsilon\mathcal{O}(z,w)}$$

and

$$S_2 - S_1 = \frac{\lambda w - \lambda\beta(\epsilon) + \epsilon\mathcal{O}(z,w)}{z - \alpha(\epsilon) + \epsilon\mathcal{O}(z,w)} - \lambda w/z$$

$$= \frac{-\lambda\beta(\epsilon)z + \lambda w\alpha(\epsilon) + \epsilon\mathcal{O}(z^2, zw, w^2)}{z(z-\alpha(\epsilon)+\epsilon\mathcal{O}(z,w))}\,.$$

If $\frac{1}{C_1}|z| \le |w| \le C_1|z|$ then $S_2 - S_1 \sim \frac{\lambda}{z^2}\left(w\alpha(\epsilon) - z\beta(\epsilon)\right)$,if $|w| > C_1|z|$ then $S_2 - S_1 \sim \frac{\epsilon w}{z^2}$ and if $|w| < \frac{1}{C_1}|z|$ then $S_2 - S_1 \sim \frac{\epsilon}{z}$.

LEMMA 21. *There is at most a uniformly bounded number of intersection points in R_{1A}.*

Proof. The case of R_{1A}, R_{1B} follows from slope estimates. For the case R_{1C}, note that leaves might be tangent when (w/z) is close to $\beta(\epsilon)/\alpha(\epsilon)$. They both have slope about λ. But since we assume that $\lambda \ne \beta'(0)/\alpha'(0)$, this tangency is at most of order 2. □

We estimate the contribution to $T \wedge_g T^\epsilon$ from R_{1A}. We assume again that $a \ne 0$. By Lemma 18, the parameters α, β are restricted to the values: $e^{-2\pi b} < |\alpha|, |\beta| < 1$, $1/C > |\beta - \alpha| > C|\epsilon|/\delta$. So fix α, β. Next, by Lemma 15, we can set $n = m$ to be some integer in the interval given by Lemma 20. The case $n = m \pm 1$ is similar. Because of the finiteness of the number of intersection points, see Lemma 21, we can set

$$p = p(n) = \frac{\log|(\beta/\alpha) - 1| + \log(1/|\epsilon|) - 2nb\pi}{a}$$

and consider only one intersection point. Then we multiply the values of $H_{\alpha,n}$ and $H_{\beta,n}$ using the formulas in case (i) or (ii) depending on whether $n < sp$ or $n > sp$. We then add these products over n and integrate the result over $d\mu(\alpha)d\mu(\beta)$.

Case (i), $n < sp$. Since $\frac{1}{2} < 1 + \frac{2sb\pi}{a} < \frac{3}{2}$, we get easily $n < n(\alpha,\beta,\epsilon) := \frac{s}{1+\frac{2sb\pi}{a}} \frac{\log|(\beta/\alpha - 1| + \log 1/|\epsilon|}{a}$.

In this case we have the following estimates at intersection points:

$$h_{\alpha,n} \sim \int_{|x|<Cv^\gamma} H_\alpha(x)|x|^{1/\gamma - 1}\left(\frac{|x|}{v^\gamma}\right)^{1-1/\gamma}\frac{1}{v}dx + \int_{|x|>Cv^\gamma} H_\alpha(x)|x|^{1/\gamma-1}\left(\frac{v^\gamma}{|x|}\right)^{1+1/\gamma}\frac{1}{v}dx\,,$$

$$h_{\beta,m} \sim \int_{|y|<C(v')^\gamma} H_\beta(y)|y|^{1/\gamma-1}\left(\frac{|y|}{(v')^\gamma}\right)^{1-1/\gamma}\frac{1}{v'}dy + \int_{|y|>C(v')^\gamma} H_\beta(y)|y|^{1/\gamma-1}\left(\frac{(v')^\gamma}{|y|}\right)^{1+1/\gamma}\frac{1}{v'}dy\,.$$

Here we have used that v and ρ are comparable. In fact from the estimate in the beginning of the section, we see that $u \sim n$, $n < sp$ so $u <\sim v$, hence $\rho \sim v$.

Here $v, v' \sim \frac{\log|(\beta/\alpha)-1| + \log 1/|\epsilon| - 2nb\pi}{a}$. This allows us to sum over v instead of over n, $\log 1/\delta < v < \log 1/|\epsilon| - C$.

We need to estimate $\sum_n h_{\alpha,n} h^\epsilon_{\beta,n}$ and then integrate the answer over the measure $\mu(\alpha)\mu(\beta)$.

Note that we will majorize the sum by the product $\sum_n h_{\alpha,n}\sum_m h^{\epsilon}_{\beta,m}$. Then we use the dominated convergence theorem. We finally have

$$\sim \sum_{v=\log 1/\delta}^{\log 1/|\epsilon|-C}\left[\int_{|x|<Cv^\gamma}\tilde H_\alpha(x)\frac{dx}{v^\gamma}+\int_{|x|>Cv^\gamma}\tilde H_\alpha(x)\frac{|v|^\gamma}{|x|^2}dx\right]$$

We split the integral

$$\begin{aligned}\sum_n h_{\alpha,n} \sim &\int_{|x|<(\log 1/\delta)^\gamma}\tilde H_\alpha(x)\sum_{v=\log 1/\delta}^{\log 1/|\epsilon|-C}\frac{dx}{v^\gamma}\\ &+\int_{(\log 1/\delta)^\gamma<|x|<(\log 1/|\epsilon|)^\gamma}\tilde H_\alpha(x)\sum_{v=|x|^{1/\gamma}}^{\log 1/|\epsilon}\frac{dx}{v^\gamma}\\ &+\int_{(\log 1/\delta)^\gamma<|x|<(\log 1/|\epsilon|)^\gamma}\tilde H_\alpha(x)\frac{1}{x^2}\sum_{v=\log 1/\delta}^{|x|^{1/\gamma}}v^\gamma dx\\ &+\int_{|x|>(\log 1/|\epsilon|)^\gamma}\tilde H_\alpha(x)\frac{1}{x^2}\sum_{v=\log 1/\delta}^{\log 1/|\epsilon}v^\gamma dx\,.\end{aligned}$$

We estimate the quantities under Σ in the right-hand side and we get

$$\begin{aligned}\sum_n h_{\alpha,n} \sim &\int_{|x|<(\log 1/\delta)^\gamma}\tilde H_\alpha(x)\frac{1}{(\log 1/\delta)^{\gamma-1}}\\ &+\int_{(\log 1/\delta)^\gamma<|x|<(\log 1/|\epsilon|)^\gamma}\tilde H_\alpha(x)\frac{1}{|x|^{1-1/\gamma}}dx\\ &+\int_{(\log 1/\delta)^\gamma<|x|<(\log 1/|\epsilon|)^\gamma}\tilde H_\alpha(x)\frac{1}{x^2}\frac{1}{|x|^{1-1/\gamma}}dx\\ &+\int_{|x|>(\log 1/|\epsilon|)^\gamma}\tilde H_\alpha(x)\frac{1}{x^2}\big(\log 1/|\epsilon|\big)^{\gamma+1}dx\,.\end{aligned}$$

Using Lemma 13 this gives

$$\begin{aligned}\sum_n h_{\alpha,n} \sim &\int_{|x|<(\log 1/\delta)^\gamma}\tilde H_\alpha(x)|x|^{1/\gamma-1}\left(\frac{|x|}{(\log 1/\delta)^\gamma}\right)^{1-1/\gamma}\\ &+\int_{(\log 1/\delta)^\gamma<|x|<(\log 1/|\epsilon|)^\gamma}\tilde H_\alpha(x)|x|^{1/\gamma-1}dx\\ &+\int_{|x|>(\log 1/|\epsilon|)^\gamma}\tilde H_\alpha(x)|x|^{1/\gamma-1}\left(\frac{(\log 1/|\epsilon|)^\gamma}{|x|}\right)^{1+1/\gamma}dx\\ &\to 0\,,\quad \text{as } \delta\to 0\,.\end{aligned}$$

Observe that we had to take δ small.

This finishes the case (i), $n<sp$. So we have proved

LEMMA 22. *The contribution to the geometric wedge product from R_{1A} in case (i), $a\neq 0$, $n<sp$ goes to zero when $\delta\to 0$.*

We next deal with the case $n>sp$. Recall that case (ii) is $a\neq 0$, $n>sp$. We then have $(u+iv)^\gamma=U+iV\sim n^\gamma+ip(n)n^{\gamma-1}$.

Then

$$H_{\alpha,n} \sim \int_{|x-n^\gamma|\le p(n)n^{\gamma-1}} \tilde H_\alpha(x)\frac{1}{p(n)n^{\gamma-1}}dx + \int_{n^\gamma/2>|x-n^\gamma|>p(n)n^{\gamma-1}} \tilde H_\alpha(x)\frac{p(n)n^{\gamma-1}}{|x-n^\gamma|^2}dx + \int_{n^\gamma/2<|x-n^\gamma|<2n^\gamma} \tilde H_\alpha(x)\frac{p(n)n^{\gamma-1}}{n^{2\gamma}}dx + \int_{|x-n^\gamma|>2n^\gamma} \tilde H_\alpha(x)\frac{p(n)n^{\gamma-1}}{x^2}dx$$
$$= \mathrm{I}_n + \mathrm{II}_n + \mathrm{III}_n + \mathrm{IV}_n\,.$$

For simplicity of notation we assume $a>0$. Then we have the following range for n from Lemma 20. The number n satisfies

$$a\log 1/\delta < \log\big|(\beta/\alpha)-1\big| + \log\big(1/|\epsilon|\big) - 2nb\pi < a\log 1/|\epsilon| - aC\,.$$

This gives

$$\log\big|(\beta/\alpha)-1\big| + \log\big(1/|\epsilon|\big) - a\log 1/|\epsilon| - aC < 2nb\pi < -a\log 1/\delta + \log\big|(\beta/\alpha)-1\big| + \log\big(1/|\epsilon|\big)\,.$$

Hence

$$\frac{\log|(\beta/\alpha)-1| + (1-a)\log(1/|\epsilon|) - aC}{2b\pi} < n < \frac{-a\log 1/\delta + \log|(\beta/\alpha)-1| + \log(1/|\epsilon|)}{2b\pi}\,.$$

However, n is further restricted because $n>sp$ and $p>\log 1/\delta$. If we then estimate IV_n and sum over n, we get

$$\sum_n \mathrm{IV}_n <\sim \int_{|x|>(\log 1/\delta)^\gamma} \tilde H_\alpha(x)\frac{1}{x^2}\sum_{n=\log 1/\delta}^{|x|^{1/\gamma}} n^\gamma <\sim \int_{|x|>(\log 1/\delta)^\gamma} \tilde H_\alpha(x)|x|^{1/\gamma-1}dx \to 0\,.$$

Similarly for $\sum_n \mathrm{III}_n$ we get to estimate $\sum 1/n^\gamma <\sim |x|^{1/\gamma-1}$ which again is fine.

Next we handle the terms II_n. For a given x, the range of n is on the order of $2/3|x|^{1/\gamma} < n < |x|^{1/\gamma} - p(x^{1/\gamma})$ and similarly for $n>|x|^{1/\gamma}$. Also note that the terms $p(n)\lesssim |x|^{1/\gamma}$ since $n\sim |x|^{1/\gamma}$ and $p\lesssim n$. So we sum the expressions $\frac{n^{\gamma-1}}{(x-n^\gamma)^2}$ which integrates to $\frac{1}{|x-n^\gamma|}$, so inserting the limits of the summation, we get a bound of the same form as for III_n.

Finally we sum over the I_n. Here we make the rough estimate that $\log 1/\delta < p(n) < sn$. So we integrate over $|x-n^\gamma|<sn^\gamma$ but in the integrand we replace $p(n)$ by $\log 1/\delta$. With this estimate we get the integral $\tilde H_\alpha(x)\frac{1}{\log(1/\delta)|x|} \ll \tilde H_\alpha(x)|x|^{1/\gamma-1}$. Hence this also goes to zero with δ.

Finally, we have shown the following:

Lemma 23. *The contribution to the geometric wedge product in the case of R_{1A}, case (ii), $a\neq 0$, $n>sp$ goes to zero when $\delta\to 0$.*

9 Theorem 7 for R_{1C}, the Diagonal Part of R_1

We are in the set $\{C|\epsilon| < |z|,\ |w| < \delta,\ |z| \sim |w|\}$. On $L_{\alpha,n}$, we have the following estimate for u, v:

$$2n\pi < u < 2(n+1)\pi\,, \quad \left|v - \frac{2n}{1-a}\right| < C'',\ \log\frac{1}{\delta} < v < \log\left(\frac{1}{|\epsilon|}\right) - C\,.$$

In the U, V coordinates, $(u+iv)^\gamma = U + iV$, $V \sim |n|^\gamma$, $|U| <\sim |n|^\gamma$.

So at intersection points

$$h_{\alpha,n} \sim \int \tilde{H}_\alpha(x)\frac{n^\gamma}{n^{2\gamma} + (x-U)^2}dx$$
$$\sim \int_{|x|<2n^\gamma} \tilde{H}_\alpha(x)\frac{dx}{n^\gamma} + \int_{|x|>2n^\gamma} \tilde{H}_\alpha(x)\frac{n^\gamma dx}{x^2}\,.$$

Adding up the contributions

$$\sum_n h_{\alpha,n} \sim \int_{|x|<(\log(1/|\delta|))^\gamma} \tilde{H}_\alpha(x)\bigg(\sum_{n=\log 1/\delta}^{\infty} \frac{1}{n^\gamma}\bigg)dx$$
$$+ \int_{|x|>(\log(1/|\delta|))^\gamma} \tilde{H}_\alpha(x)\bigg(\sum_{n=x^{1/\gamma}} \frac{1}{n^\gamma}\bigg)dx$$
$$+ \int_{|x|>(\log(1/|\delta|))^\gamma} \tilde{H}_\alpha(x)\bigg(\sum_{n=\log 1/\delta}^{x^{1/\gamma}} \frac{n^\gamma}{x^2}\bigg)dx\,.$$

After estimating the sums we get

$$\sum_n h_{\alpha,n} \sim \int_{|x|<(\log(1/|\delta|))^\gamma} \tilde{H}_\alpha(x)\frac{1}{(\log(1/\delta))^\gamma}dx + \int_{|x|>(\log(1/|\delta|))^\gamma} \tilde{H}_\alpha(x)\frac{1}{(x^{1/\gamma})^{\gamma-1}}dx$$
$$+ \int_{|x|>(\log(1/|\delta|))^\gamma} \tilde{H}_\alpha(x)\frac{(x^{1/\gamma})^{\gamma+1}}{x^2}dx\,.$$

So,

$$\sum_n h_{\alpha,n} \sim \int_{|x|>(\log(1/\delta))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}dx$$
$$+ \int_{|x|<(\log(1/\delta))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\left(\frac{|x|}{(\log(1/\delta))^\gamma}\right)^{1-1/\gamma} dx\,.$$

This is arbitrarily small as long as δ is chosen small enough.

10 Theorem 7 for R_2, the Part of D_3 Close to the z-Axis

This case is divided in two subcases depending on whether one is close to one of the separatrices (R_{2A}) or not (R_{2B}).

11 Theorem 7 for R_{2A} Close to a Separatrix

Again we assume that $a \neq 0$. There are two separatrices, $w = 0$ and w close to $\beta(\epsilon)$. By symmetry it suffices to do one of them. We choose to estimate close to the separatrix $w = 0$. So we set $R_{2A} = \{C|\epsilon| < |z| < \delta, |w| < s|\epsilon|\}$ for some small constant $s > 0$. Let $L^\epsilon_{\beta,m}$ and $L_{\alpha,n}$ be plaques intersecting at (z, w) in R_{2A} for parameters $(u', v'), (u, v)$.

Since the point (z, w) is about distance $|\beta'(0)||\epsilon|$ away from the separatrix for the perturbed lamination, we get $(w' = \beta(\epsilon) + \beta e^{i\lambda(u'+(\log|\beta|/b)+iv')} + \cdots)$. This gives

$$2m\pi < u' < 2(m+1)\pi \quad \text{and} \quad C_1 < av' + 2mb\pi + \log|\epsilon| < C_2 \,.$$

We also have

$$C|\epsilon| < |z| = e^{-v} = |z'| = \left|\alpha(\epsilon) + e^{i(u'+\log|\beta|/b)-v'} + \cdots\right| ,$$

hence $C_3 < v - v' < C_4$, $C_4 < av + 2mb\pi + \log|\epsilon| < C_5$ and $2n\pi < u < 2(n+1)\pi$.

Using $|w| < s|\epsilon|$, we get $\log(1/s) < av + 2nb\pi + \log|\epsilon|$, $2(n-m)b\pi = (av + 2nb\pi + \log|\epsilon|) - (av + 2m\pi b + \log|\epsilon|) > \log(1/s) - C_1$.

These calculations show that for the given plaques, the pairs $(u, v), (u', v')$ belong to rectangles of uniformly bounded size. Hence the number of intersection points can easily be estimated by using slope estimates for the plaques. We get a uniformly bounded number of intersection points.

We divide this into cases I, II, III.

For I we have $1/C \log(1/|\epsilon|) < 2mb\pi + \log|\epsilon| < C \log(1/|\epsilon|)$.

For II we have $2mb\pi + \log|\epsilon| < 1/C \log(1/|\epsilon|)$.

For III we have $2mb\pi + \log|\epsilon| > C \log(1/|\epsilon|)$. We note however, that in case III, v' must be very large in comparison with $\log 1/|\epsilon|$. This implies that $|z'| \ll |\epsilon|$ hence there are no intersection points in this case. So we are left with the two cases R_{2AI}, R_{2AII}.

12 Theorem 7 for R_{2AI} Close to a Separatrix

It follows in this case that $v, v' \sim \log(1/|\epsilon|)$. Hence

$$u' + iv' \sim 2m\pi + i\log\big(1/|\epsilon|\big) \quad \text{and} \quad U' + iV' \sim U' + i\big(\log(1/|\epsilon|)\big)^\gamma.$$

In particular $|U'| <\sim (\log(1/|\epsilon|))^\gamma$. Using the Poisson integral we estimate

$$h^\epsilon_{\beta,m} \sim \int_{|y|<2(\log(1/|\epsilon|))^\gamma} \tilde{H}_\beta(y) \frac{1}{(\log(1/|\epsilon|))^\gamma} dy + \int_{|y|>2(\log(1/|\epsilon|))^\gamma} \tilde{H}_\beta(y) \frac{(\log(1/|\epsilon|))^\gamma}{y^2} dy \,.$$

Adding up

$$\sum_{m\in \mathrm{I}} h^\epsilon_{\beta,m} \sim \int_{|y|<2(\log(1/|\epsilon|))^\gamma} \tilde{H}_\beta(y)|y|^{1/\gamma-1} \left(\frac{|y|}{(\log(1/|\epsilon|))^\gamma}\right)^{1-1/\gamma} dy$$
$$+ \int_{|y|>2(\log(1/|\epsilon|))^\gamma} \tilde{H}_\beta(y)|y|^{1/\gamma-1} \left(\frac{(\log(1/|\epsilon|))^\gamma}{|y|}\right)^{1/\gamma+1} dy \,.$$

Next we estimate $h_{\alpha,n}$. There are two cases to consider,

(a) $n < C\log(1/|\epsilon|)$;
(b) $n > C\log(1/|\epsilon|)$.

The contribution for case (a) is

Case R_{2AIa}: Recall that we have $n > m - C_6$. Hence we have that $|n| < C\log(1/|\epsilon|)$. This means that we can write $u + iv \sim 2n\pi + i(\log(1/|\epsilon|))$. Hence the estimates work as for $h^{\epsilon}_{\beta,m}$. We get

$$\sum_{|n|<C\log(1/|\epsilon|)} h_{\alpha,n} \sim \int_{|x|<2(\log(1/|\epsilon|))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\left(\frac{|x|}{(\log(1/|\epsilon|))^\gamma}\right)^{1-1/\gamma} dx + \int_{|x|>2(\log(1/|\epsilon|))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\left(\frac{(\log(1/|\epsilon|))^\gamma}{|x|}\right)^{1/\gamma+1} dx\,.$$

Case R_{2AIb}: We have $u + iv \sim n + i\log(1/|\epsilon|)$, $U + iV \sim n^\gamma + in^{\gamma-1}\log(1/|\epsilon|)$, and $h_{\alpha,n} \sim \int \tilde{H}_\alpha(x)\frac{n^{\gamma-1}\log(1/|\epsilon|)}{(n^{\gamma-1}\log(1/|\epsilon|))^2+(x-n^\gamma)^2}dx$.

This integral has already been estimated. See the calculations for the set D_1 in the region where $|z-\eta| < d|\eta|$, case (ii) where $n > 10\log(1/|\eta|)$. It follows that the contributions from that region goes to zero with ϵ.

13 Theorem 7 for R_{2AII} close to a separatrix

We restrict for simplicity to the case $a > 0$. We can divide into three cases:

(a) $n > m > v, v'$;
(b) $n > v, v' > m$;
(c) $v, v' > n > m$.

14 Theorem 7 for R_{2AIIa} Close to a Separatrix

We have $(u+iv)^\gamma = U+iV \sim n^\gamma+ivn^{\gamma-1}$ and $(u'+iv')^\gamma = U'+iV' \sim m^\gamma+iv'm^{\gamma-1} \sim (\log 1/|\epsilon|)^\gamma + iv'(\log(1/|\epsilon|))^{\gamma-1}$ with $\log 1/\delta < v' < \log 1/|\epsilon|$.

We now estimate

$$H_\beta \sim \int \tilde{H}_\beta(y)\frac{v'(\log(1/|\epsilon|))^{\gamma-1}}{[v'(\log(1/|\epsilon|))^{\gamma-1}]^2 + (y-m^\gamma)^2}dy\,.$$

We divide the integral and estimate each term. We have

$$\begin{aligned} H_\beta \sim &\int_{|y-m^\gamma|<cv'(\log 1/|\epsilon|)^{\gamma-1}} \tilde{H}_\beta(y)\frac{1}{v'(\log(1/|\epsilon|))^{\gamma-1}}dy \\ &+ \int_{(\log 1/|\epsilon|)^\gamma/2>|y-(\log 1/|\epsilon|)^\gamma|>cv'(\log 1/|\epsilon|)^{\gamma-1}} \tilde{H}_\beta(y)\frac{v'(\log(1/|\epsilon|))^{\gamma-1}}{(y-(\log 1/|\epsilon|)^\gamma)^2}dy \\ &+ \int_{|y-(\log 1/|\epsilon|)^\gamma|>(\log 1/|\epsilon|)^\gamma/2} \tilde{H}_\beta(y)\frac{v'(\log(1/|\epsilon|))^{\gamma-1}}{(y-(\log 1/|\epsilon|)^\gamma)^2}dy\,. \end{aligned}$$

So

$$\begin{aligned} H_\beta \sim &\int_{|y-m^\gamma|<cv'(\log 1/|\epsilon|)^{\gamma-1}} \tilde{H}_\beta(y)\frac{y^{1/\gamma-1}}{v'}dy \\ &+ \int_{|y-(\log 1/|\epsilon|)^\gamma|>cv'(\log 1/|\epsilon|)^{\gamma-1}} \tilde{H}_\beta(y)\frac{v'(\log(1/|\epsilon|))^{\gamma-1}}{(y-(\log 1/|\epsilon|)^\gamma)^2}dy \\ = &H_{\beta_{1,v'}} + H_{\beta_{2,v'}}\,. \end{aligned}$$

For H_α we have

$$H_\alpha \sim \int_{|x-n^\gamma|<cvn^{\gamma-1}} \tilde{H}_\alpha(x)\frac{1}{vn^{\gamma-1}}dx + \int_{|x-n^\gamma|>cvn^{\gamma-1}} \tilde{H}_\alpha(x)\frac{vn^{\gamma-1}}{(x-n^\gamma)^2}dx\,.$$

To sum up over the intersection points, we note at first that for a given plaque $L_{\beta,m}$ there is a finite range of v' and $v-v'$ is bounded, so we can assume that there is one intersection point with $L_{\alpha,n}$ for each $n>m$. Hence we sum first over the plaques $L_{\alpha,n}$, $m<n<\infty$. We obtain

$$\sum_n \int_{|x-n^\gamma|<cvn^{\gamma-1}} \tilde{H}_\alpha(x)\frac{1}{vn^{\gamma-1}}dx \sim \int_{x>m^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}dx\,.$$

The other contribution is

$$\sum_n \int_{|x-n^\gamma|>cvn^{\gamma-1}} \tilde{H}_\alpha(x)\frac{vn^{\gamma-1}}{(x-n^\gamma)^2}dx \sim \int_{x>m^\gamma-cvm^{\gamma-1}} \tilde{H}_\alpha(x)|x|^{1/\gamma-1} + \int_{x<m^\gamma-cvm^{\gamma-1}} \tilde{H}_\alpha(x)\frac{v}{|x-m^\gamma|}dx\,,$$

so, we conclude

$$\sum_{n>m} H_\alpha \sim \int_{x>m^\gamma} \tilde{H}(x)|x|^{1/\gamma-1} + \int_{x<m^\gamma-cvm^{\gamma-1}} \tilde{H}_\alpha(x)\frac{v}{|x-m^\gamma|}dx$$
$$<\sim \int_{|x|>m^\gamma/2} \tilde{H}_\alpha|x|^{1/\gamma-1} + \int_{|x|<m^\gamma/2} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\left(\frac{|x|}{m^\gamma}\right)^{1-1/\gamma}dx\,.$$

In this case m will have approximately the range $(\log 1/|\epsilon|)/2 < m < \log 1/|\epsilon|$, hence we have

$$\sum_{n>m} H_\alpha <\sim \int_{|x|>(\log 1/|\epsilon|)^\gamma} \tilde{H}_\alpha|x|^{1/\gamma-1} + \int_{|x|<(\log 1/|\epsilon|)^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\left(\frac{|x|}{(\log 1/|\epsilon|)^\gamma}\right)^{1-1/\gamma}dx\,.$$

Next we sum H_β over m or equivalently over v', $\log 1/\delta < v' < (\log 1/|\epsilon|)/2$. We integrate first over $H_{\beta_{1,v'}}$. For a given y, the range of v' is in the interval with endpoints $(1\pm c)\frac{y-(\log 1/|\epsilon|)^\gamma}{(\log 1/|\epsilon|)^{\gamma-1}}$. This part is bounded by

$$\int_{|y-(\log 1/|\epsilon|)^\gamma|<(\log 1/|\epsilon|)^\gamma/2} \tilde{H}_\beta(y)|y|^{1/\gamma-1}dy \to 0\,.$$

The second part is bounded by

$$\int_{|y|<2(\log 1/|\epsilon|)^\gamma} \tilde{H}_\beta(y)|y|^{1/\gamma-1}\left(\frac{|y|}{(\log 1/|\epsilon|)^\gamma}\right)^{1-1/\gamma}dy + \int_{|y|>2(\log 1/|\epsilon|)^\gamma} \tilde{H}_\beta(y)|y|^{1/\gamma-1}\left(\frac{(\log 1/|\epsilon|)^\gamma}{|y|}\right)^{1+1/\gamma}dy\,.$$

Again the contribution goes to zero by Proposition 1 and Lemma 13.

15 Theorem 7 for R_{2AIIb} Close to a Separatrix

In this case $n > v, v' > m$. First we recall the estimates for H_α which are the same as in the case R_{2AIIa}. We have $(u+iv)^\gamma = U+iV \sim n^\gamma + ivn^{\gamma-1}$ with

$\log 1/\delta < v, v' < \log 1/|\epsilon|$. So

$$H_\alpha \sim \int_{|x-n^\gamma|<cvn^{\gamma-1}} \tilde{H}_\alpha(x)\frac{1}{vn^{\gamma-1}}dx + \int_{|x-n^\gamma|>cvn^{\gamma-1}} \tilde{H}_\alpha(x)\frac{vn^{\gamma-1}}{(x-n^\gamma)^2}dx\,.$$

Next we estimate H_β. We have $(u'+iv')^\gamma = U'+iV'$ with $(\log 1/|\epsilon|)/2 < v' < \log 1/|\epsilon|$ and $m+v' = \log 1/|\epsilon|$. Hence $V' \sim (\log 1/|\epsilon|)^\gamma$ and $|U'| <\sim (\log 1/|\epsilon|)^\gamma$.

We get $H_\beta \sim \int_{|y|<2(\log 1/|\epsilon|)^\gamma} \tilde{H}_\beta \frac{1}{(\log 1/|\epsilon|)^\gamma}dy + \int_{|y|>2(\log 1/|\epsilon|)^\gamma} \tilde{H}_\beta \frac{(\log 1/|\epsilon|)^\gamma}{y^2}dy$.

Next we estimate the contribution to the geometric wedge product. So fix α, β. Next fix a plaque $L_{\beta,m}$, $v, v' \sim \log 1/|\epsilon| - m$. Then we consider the contribution from H_α for all $n > v$. This is the same estimate as in the previous section, so goes to zero when $\epsilon \to 0$. To sum up over m, notice that we have about $\log 1/|\epsilon|$ terms of the same order of magnitude. From this we get that the contribution goes to zero when $\epsilon \to 0$.

To estimate the geometric wedge product, we sum independently over n, m throwing out the condition that $n > m$. We get as in the previous section that the contribution goes to zero.

16 Theorem 7 for R_{2AIIc} Close to a Separatrix

Here we deal with the case when $v, v' > n > m$. In this case the same formula as in the last section applies to both H_α and H_β. We have

$$H_\alpha \sim \int_{|x|<2(\log 1/|\epsilon|)^\gamma} \tilde{H}_\alpha \frac{1}{(\log 1/|\epsilon|)^\gamma}dx + \int_{|x|>2(\log 1/|\epsilon|)^\gamma} \tilde{H}_\alpha \frac{(\log 1/|\epsilon|)^\gamma}{x^2}dx\,,$$

and

$$H_\beta \sim \int_{|y|<2(\log 1/|\epsilon|)^\gamma} \tilde{H}_\beta \frac{1}{(\log 1/|\epsilon|)^\gamma}dy + \int_{|y|>2(\log 1/|\epsilon|)^\gamma} \tilde{H}_\beta \frac{(\log 1/|\epsilon|)^\gamma}{y^2}dy\,.$$

So again the contribution goes to zero.

17 Theorem 7 for R_{2B} away from the Separatrices

At an intersection point $p = (z, w)$ of $L_{\alpha,n}, L^\epsilon_{\beta,m}$ we have $s|\epsilon| < |w| < C|\epsilon|$ and $s|\epsilon| < |w - \beta(\epsilon)| < C|\epsilon|$. So $\log|\epsilon| - C < -av - bu < \log|\epsilon| + C$ and $\log|\epsilon| - C < -av' - bu' < \log|\epsilon| + C$. This gives $-C < v - v' < C$, $-C < n - m < C$ and $\log(1/\delta) < v, v' < \log(1/|\epsilon|) - C$, $-C\log(1/|\epsilon|) < u, u', n, m < C\log(1/|\epsilon|)$.

Given (α, β, n, m) we need to estimate the values of v, v' corresponding to an intersection, as well as the number of intersections. The following is immediate. There is no dependence on α, β.

Lemma 24. *At intersection points of $L_{\alpha,n}, L^\epsilon_{\beta,m}$ in R_{2B} away from the separatrices, we have*

$$-2nb\pi/a + 1/a\log\big(1/|\epsilon|\big) - C < v, v' < -2nb\pi/a + 1/a\log\big(1/|\epsilon|\big) + C\,.$$

It follows that intersection points are localized in bounded rectangles. To show finiteness of number of intersection points for given plaques, we use slope estimates.

We divide the estimates in two cases, (i) if $v, v' \sim \log(1/|\epsilon|)$ and (ii) if $\log(1/\delta) < v, v' < 1/C\log(1/|\epsilon|)$.

18 Theorem 7 for R_{2Bi} when $v \sim \log(1/|\epsilon|)$

Recall that this means that for a large constant A, $\frac{1}{A}\log\frac{1}{|\epsilon|} < v < A\log\frac{1}{|\epsilon|}$. The estimates for $h_{\alpha,n}$ and $h^{\epsilon}_{\beta,m}$ are similar. We have $U+iV=(u+iv)^{\gamma} \sim U+i(\log(1/|\epsilon|))^{\gamma}$. So $|U| \lesssim (\log(1/|\epsilon|))^{\gamma}$.

At intersection points

$$\begin{aligned} h_{\alpha,n} &\sim \int \tilde{H}_{\alpha}(x)\frac{(\log(1/|\epsilon|))^{\gamma}}{(\log(1/|\epsilon|))^{2\gamma}+(x-U)^2}dx \\ &\sim \int_{|x|<C(\log(1/|\epsilon|))^{\gamma}} \tilde{H}_{\alpha}|x|^{1/\gamma-1}\left(\frac{|x|}{(\log(1/|\epsilon|))^{\gamma}}\right)^{1-1/\gamma}\frac{1}{\log(1/|\epsilon|)}dx \\ &\quad + \int_{|x|>C(\log(1/|\epsilon|))^{\gamma}} \tilde{H}_{\alpha}|x|^{1/\gamma-1}\left(\frac{(\log(1/|\epsilon|))^{\gamma}}{|x|}\right)^{1+1/\gamma}\frac{1}{\log(1/|\epsilon|)}dx\,. \end{aligned}$$

We estimate the total contribution,

$$\begin{aligned} \sum_n h_{\alpha,n} &\sim \int_{|x|<C(\log(1/|\epsilon|))^{\gamma}} \tilde{H}_{\alpha}|x|^{1/\gamma-1}\left(\frac{|x|}{(\log(1/|\epsilon|))^{\gamma}}\right)^{1-1/\gamma}dx \\ &\quad + \int_{|x|>C(\log(1/|\epsilon|))^{\gamma}} \tilde{H}_{\alpha}|x|^{1/\gamma-1}\left(\frac{(\log(1/|\epsilon|))^{\gamma}}{|x|}\right)^{1+1/\gamma}dx\,, \end{aligned}$$

which will converge to 0 by Proposition 1.

19 Theorem 7 for R_{2Bii} when $v < \frac{1}{A}\log(1/|\epsilon|)$

In this case we have $u,u',n,m \sim \log(1/|\epsilon|)$. The estimates for $h_{\alpha,n}, h^{\epsilon}_{\beta,m}$ are similar. In the following $0 < d \ll 1$. More precisely, d will be close to $|a|A$, see the 4th inequality below. Expressing that we are in R_{2Bii} we get the following inequalities:

$$\begin{gathered} (1-d)\log\big(1/|\epsilon|\big) < 2nb\pi < (1+d)\log\big(1/|\epsilon|\big)\,, \\ \log|\epsilon| - C < -av - bu < \log|\epsilon| + C\,. \end{gathered}$$

Hence

$$\begin{gathered} \log|\epsilon| + 2nb\pi - C < -av < \log|\epsilon| + 2bn\pi + C\,, \\ -d\log\big(1/|\epsilon|\big) - C < -av < d\log\big(1/|\epsilon|\big) + C\,. \end{gathered}$$

In U,V coordinates, $U+iV=(u+iv)^{\gamma} \sim (\log(1/|\epsilon|))^{\gamma} + i(\log(1/|\epsilon|))^{\gamma-1}v$.

This gives $h_{\alpha,n} \sim \int \tilde{H}_{\alpha}(x)\frac{(\log(1/|\epsilon|))^{\gamma-1}v}{((\log(1/|\epsilon|))^{\gamma-1}v)^2+(x-U)^2}dx$.

When we sum up over $h_{\alpha,n}, h^{\epsilon}_{\beta,m}$ we can take for simplicity $n=m$ and $v=v'$ since $|n-m|, |v-v'|$ are uniformly bounded in R_{2B} as stated above. The product of contributions is estimated by

$$\begin{aligned} h_{\alpha,n}h^{\epsilon}_{\beta,m} &\sim \int \tilde{H}_{\alpha}(x)\frac{(\log(1/|\epsilon|))^{\gamma-1}v}{((\log(1/|\epsilon|))^{\gamma-1}v)^2+(x-U)^2}dx \\ &\quad * \int \tilde{H}_{\beta}(y)\frac{(\log(1/|\epsilon|))^{\gamma-1}v}{((\log(1/|\epsilon|))^{\gamma-1}v)^2+(y-U)^2}dy\,. \end{aligned}$$

So

$$h_{\alpha,n}h^{\epsilon}_{\beta,m} \sim \Big[\int_{|x-U|<(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}_\alpha(x)\frac{1}{(\log(1/|\epsilon|))^{\gamma-1}v}dx + \int_{|x-U|>(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}\alpha(x)\frac{(\log(1/|\epsilon|))^{\gamma-1}v}{(x-U)^2}dx\Big] * \Big[\int_{|y-U|<(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}_\beta(y)\frac{1}{(\log(1/|\epsilon|))^{\gamma-1}v}dy + \int_{|y-U|>(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}_\beta(y)\frac{(\log(1/|\epsilon|))^{\gamma-1}v}{(y-U)^2}dy\Big] = [\mathrm{I}+\mathrm{II}][\mathrm{III}+\mathrm{IV}]\,.$$

There are 4 cases to sum over: (I, III), (II, III), (II, IV) and (I, IV). The case (I, IV) is similar to (II, III) so we can skip it without any loss.

20 Theorem 7 for $R_{2Bii(\mathrm{I,III})}$

We have

$$h_{\alpha,n}h^{\epsilon}_{\beta,m} \sim \frac{1}{v^2}\int_{|x-U|<1/C(\log(1/|\epsilon|))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}dx * \int_{|y-U|<1/C(\log(1/|\epsilon|))^\gamma} \tilde{H}_\beta(y)|y|^{1/\gamma-1}dy\,.$$

Since $\log(1/\delta) < v < 1/A\log(1/|\epsilon|)$ we get

$$\sum h_{\alpha,n}h^{\epsilon}_{\beta,m} \lesssim \frac{1}{\log(1/\delta)}\int_{|x-U|<1/C(\log(1/|\epsilon|))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}dx * \int_{|y-U|<1/C(\log(1/|\epsilon|))^\gamma} \tilde{H}_\beta(y)|y|^{1/\gamma-1}dy\,.$$

Finally,

$$\sum h_{\alpha,n}h^{\epsilon}_{\beta,m} \lesssim \frac{1}{\log(1/\delta)}\int_{|x-(\log(1/|\epsilon|))^\gamma|<1/C(\log(1/|\epsilon|))^\gamma} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}dx * \int_{|y-(\log(1/|\epsilon|))^\gamma|<1/C(\log(1/|\epsilon|))^\gamma} \tilde{H}_\beta(y)|y|^{1/\gamma-1}dy\,.$$

This contribution goes to zero when $\epsilon \to 0$.

21 Theorem 7 for $R_{2Bii(\mathrm{II,III})}$

We estimate

$$h_{\alpha,n}h^{\epsilon}_{\beta,m} \sim \int_{|x-U|>(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}_\alpha(x)\frac{(\log(1/|\epsilon|))^{\gamma-1}v}{(x-U)^2}dx * \int_{|y-U|<(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}_\beta(y)\frac{1}{(\log(1/|\epsilon|))^{\gamma-1}v}dy\,.$$

Here $\log(1/\delta) < v < d\log(1/|\epsilon|)$, $0 < d \ll 1$ and $-av = \log|\epsilon| + 2bn\pi + \mathcal{O}(1)$. Also we can take $n = m$. When we sum over n, v runs through $\log(1/\delta) < v < d\log(1/|\epsilon|)$.

Hence the contribution to the geometric wedge product is

$$\sum_{n,m} h_{\alpha,n} h^{\epsilon}_{\beta,m} \sim \sum_{v=\log(1/\delta)}^{d\log(1/|\epsilon|)} \int_{|x-(\log(1/|\epsilon|))^\gamma|>(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}_\alpha(x) \frac{1}{(x-(\log(1/|\epsilon|)^\gamma)^2} dx$$
$$* \int_{|y-(\log(1/|\epsilon|))^\gamma|<(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}_\beta(y) dy \, .$$

We introduce a counting function, $N(x,y)$, which tells us for a given (x,y) for how many terms of the sum (x,y) is in the domain of integration for the above integrals:

$$\big|x-(\log(1/|\epsilon|))^\gamma\big| > \big(\log(1/|\epsilon|)\big)^{\gamma-1}|v|$$
$$|y-(\log(1/|\epsilon|))^\gamma\big| < \big(\log(1/|\epsilon|)\big)^{\gamma-1}|v| \, .$$

We divide the above domain in three parts:

$$P_1 = \big\{|x-(\log(1/|\epsilon|))^\gamma| > d(\log(1/|\epsilon|))^\gamma, \quad \big|y-(\log(1/|\epsilon|))^\gamma\big| < \log(1/\delta)(\log(1/|\epsilon|))^{\gamma-1}\big\}$$

in which case $N_1(x,y) \sim d\log(1/|\epsilon|)$,

$$P_2 = \big\{|x-(\log(1/|\epsilon|))^\gamma| > d(\log(1/|\epsilon|))^\gamma, \quad \log(1/\delta)(\log(1/|\epsilon|))^{\gamma-1} < |y-(\log(1/|\epsilon|))^\gamma| < d(\log(1/|\epsilon|))^\gamma\big\} \, ,$$

for the P_2 case $N_2(x,y) \sim \frac{d(\log(1/|\epsilon|))^\gamma - |y-(\log(1/|\epsilon|))^\gamma|}{(\log(1/|\epsilon|))^{\gamma-1}}$. Finally,

$$P_3 = \big\{\log(1/\delta)(\log(1/|\epsilon|))^{\gamma-1} < |x-(\log(1/|\epsilon|))^\gamma| < d(\log(1/|\epsilon|))^\gamma, \quad \log(1/\delta)(\log(1/|\epsilon|))^{\gamma-1} < |y-(\log(1/|\epsilon|))^\gamma| < d(\log(1/|\epsilon|))^\gamma\big\} \, .$$

For P_3,

$$N_3(x,y) \sim \frac{|x-(\log(1/|\epsilon|))^\gamma| - |y-(\log(1/|\epsilon|))^\gamma|}{(\log(1/|\epsilon|))^{\gamma-1}}$$

when the right-hand side is positive. Hence,

$$N_3(x,y) \sim \frac{|x-y|}{(\log(1/|\epsilon|))^{\gamma-1}} \, .$$

22 Theorem 7 for $R_{2Bii(\mathrm{II},\mathrm{III})P_1}$

This gives the estimate for the product

$$\begin{aligned}
\sum_{n,m} h_{\alpha,n} h^{\epsilon}_{\beta,m} &\sim d\log\big(1/|\epsilon|\big) \int_{P_1} \frac{\tilde{H}_\alpha(x)\tilde{H}_\beta(y)}{(x-(\log(1/|\epsilon|))^\gamma)^2} dxdy \\
&\sim \int_{P_1} \frac{\tilde{H}_\alpha(x)|x|^{1/\gamma-1}|x|^{1-1/\gamma}\tilde{H}_\beta(y)|y|^{1/\gamma-1}}{|x-(\log(1/|\epsilon|))^\gamma|^{1-1/\gamma}((\log(1/|\epsilon|)^\gamma)^{2/\gamma}} \log(1/|\epsilon|) \\
&\lesssim \int_{P_1} \tilde{H}_\alpha(x)|x|^{1/\gamma-1}\tilde{H}_\beta(y)|y|^{1/\gamma-1} \frac{1}{\log(1/|\epsilon|)} \\
&\to 0 \, ,
\end{aligned}$$

when $\epsilon \to 0$.

23 Theorem 7 for $R_{2Bii(\mathrm{II},\mathrm{III})P_2}$

We get the estimate

$$\sum_{n,m} h_{\alpha,n} h^{\epsilon}_{\beta,m} \sim \int_{P_2} \frac{\tilde H_\alpha(x)|x|^{1/\gamma-1}\tilde H_\beta(y)|y|^{1/\gamma-1}}{(x-(\log(1/|\epsilon|))^\gamma)^2}|x|^{1-1/\gamma}|y|^{1-1/\gamma} * \frac{d(\log(1/|\epsilon|))^\gamma - |y-(\log(1/|\epsilon|))^\gamma|}{(\log(1/|\epsilon|))^{\gamma-1}} dxdy\,.$$

Using the definition of P_2,

$$\begin{aligned}\sum_{n,m} h_{\alpha,n} h^{\epsilon}_{\beta,m} &\sim \int_{P_2} \tilde H_\alpha(x)|x|^{1/\gamma-1}\tilde H_\beta(y)|y|^{1/\gamma-1}\frac{|x|}{|x-(\log(1/|\epsilon|))^\gamma|}|x|^{-1/\gamma} \\ &\quad * \frac{(d(\log(1/|\epsilon|))^\gamma - |y-(\log(1/|\epsilon|))^\gamma|)}{|x-(\log(1/|\epsilon|))^\gamma|} dxdy \\ &<\sim \int_{P_2} \tilde H_\alpha(x)|x|^{1/\gamma-1}\tilde H_\beta(y)|y|^{1/\gamma-1}\frac{1}{\log(1/|\epsilon|)}dxdy \\ &\to 0\,,\end{aligned}$$

as $\epsilon \to 0$.

24 Theorem 7 for $R_{2Bii(\mathrm{II},\mathrm{III})P_3}$

We estimate, using the definition of P_3, the sum,

$$\begin{aligned}\sum_{n,m} h_{\alpha,n} h^{\epsilon}_{\beta,m} &\sim \int_{P_3} \frac{\tilde H_\alpha(x)\tilde H_\beta(y)}{(x-(\log(1/|\epsilon|))^\gamma)^2}\frac{|x-y|}{(\log(1/|\epsilon|))^{\gamma-1}}dxdy \\ &\sim \int_{P_3} \tilde H_\alpha(x)|x|^{1/\gamma-1}\tilde H_\beta(y)|y|^{1/\gamma-1} \\ &\quad * \frac{|x-y|}{(x-(\log(1/|\epsilon|))^\gamma)^2(\log(1/|\epsilon|))^{1-\gamma}}dxdy\,.\end{aligned}$$

Hence,

$$\begin{aligned}\sum_{n,m} h_{\alpha,n} h^{\epsilon}_{\beta,m} &<\sim \int_{P_3} \tilde H_\alpha(x)|x|^{1/\gamma-1}\tilde H_\beta(y)|y|^{1/\gamma-1} \\ &\quad * \frac{1}{|x-(\log(1/|\epsilon|))^\gamma|(\log(1/|\epsilon|))^{1-\gamma}}dxdy \\ &<\sim \int_{P_3} \tilde H_\alpha(x)|x|^{1/\gamma-1}\tilde H_\beta(y)|y|^{1/\gamma-1} \\ &\quad * \frac{1}{\log(1/\delta)(\log(1/|\epsilon|))^{\gamma-1}(\log(1/|\epsilon|))^{1-\gamma}}dxdy \\ &\sim \frac{1}{\log(1/\delta)}\int_{R_3} \tilde H_\alpha(x)|x|^{1/\gamma-1}\tilde H_\beta(y)|y|^{1/\gamma-1}dxdy \to 0\,,\end{aligned}$$

because we can choose δ small enough.

25 Theorem 7 for $R_{2Bii(\mathrm{II},\mathrm{IV})}$

Recall from Lemma 24 that

$$-2nb\pi/a + 1/a\log\big(1/|\epsilon|\big) - C < v, v' < -2nb\pi/a + 1/a\log\big(1/|\epsilon|\big) + C\,.$$

We estimate the contribution

$$h_{\alpha,n}h^{\epsilon}_{\beta,m} \sim \int_{|x-(\log(1/|\epsilon|))^{\gamma}|>(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}_{\alpha}(x)\frac{(\log(1/|\epsilon|))^{\gamma-1}v}{(x-(\log(1/|\epsilon|))^{\gamma})^2}dx$$
$$* \int_{|y-(\log(1/|\epsilon|))^{\gamma}|>(\log(1/|\epsilon|))^{\gamma-1}|v|} \tilde{H}_{\beta}(y)\frac{(\log(1/|\epsilon|))^{\gamma-1}v}{(y-(\log(1/|\epsilon|))^{\gamma})^2}dy\,.$$

Note that when we sum over n, v depends linearly on n and as seen above, ranges from $\log 1/\delta$ to $d\log(1/|\epsilon|)$, $0<d\ll 1$.

Hence we need to estimate the expression $I(\alpha,\beta)$for given (α,β):

$$\mathrm{I}(\alpha,\beta) := \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} \int_{|x-(\log(1/|\epsilon|))^{\gamma}|>(\log(1/|\epsilon|))^{\gamma-1}k} \tilde{H}_{\alpha}(x)\frac{(\log(1/|\epsilon|))^{\gamma-1}k}{(x-(\log(1/|\epsilon|))^{\gamma})^2}dx$$
$$* \int_{|y-(\log(1/|\epsilon|))^{\gamma}|>(\log(1/|\epsilon|))^{\gamma-1}k} \tilde{H}_{\beta}(y)\frac{(\log(1/|\epsilon|))^{\gamma-1}k}{(y-(\log(1/|\epsilon|))^{\gamma})^2}dy\,.$$

We introduce the integrals

$$\mathrm{I}_{j,\alpha} := \int_{(\log(1/|\epsilon|))^{\gamma-1}j<|x-(\log(1/|\epsilon|))^{\gamma}|<(\log(1/|\epsilon|))^{\gamma-1}(j+1)} \tilde{H}_{\alpha}(x)\frac{(\log(1/|\epsilon|))^{\gamma-1}}{(x-(\log(1/|\epsilon|))^{\gamma})^2}dx$$
$$\sim \frac{1}{j^2}\int_{(\log(1/|\epsilon|))^{\gamma-1}j<|x-(\log(1/|\epsilon|))^{\gamma}|<(\log(1/|\epsilon|))^{\gamma-1}(j+1)} \tilde{H}_{\alpha}(x)|x|^{1/\gamma-1}dx = \frac{1}{j^2}\hat{I}_{j,\alpha}\,,$$

and

$$\mathrm{I}_{\infty,\alpha} := \int_{|x-(\log(1/|\epsilon|))^{\gamma}|>d(\log(1/|\epsilon|))^{\gamma}} \tilde{H}_{\alpha}(x)\frac{(\log(1/|\epsilon|))^{\gamma-1}}{(x-(\log(1/|\epsilon|))^{\gamma})^2}dx$$
$$<\sim \frac{1}{(\log(1/|\epsilon|))^2}\int \tilde{H}_{\alpha}(x)|x|^{1/\gamma-1}dx = I^1_{\infty,\alpha}\,,$$

and similarly for β. We get

$$\mathrm{I}(\alpha,\beta) = \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)}\left[k\left(\left(\sum_{j=k}^{d\log(1/|\epsilon|)} I_{j,\alpha}\right)+\mathrm{I}_{\infty,\alpha}\right)\right]\left[k\left(\left(\sum_{i=k}^{d\log(1/|\epsilon|)} I_{i,\beta}\right)+I_{\infty,\beta}\right)\right]$$
$$\sim \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} k^2\left[\left(\left(\sum_{j=k}^{d\log(1/|\epsilon|)}\frac{\hat{I}_{j,\alpha}}{j^2}\right)+\mathrm{I}_{\infty,\alpha}\right)\right]\left[\left(\left(\sum_{i=k}^{d\log(1/|\epsilon|)}\frac{\hat{I}_{i,\beta}}{i^2}\right)+\mathrm{I}_{\infty,\beta}\right)\right]$$
$$= \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} k^2\left[\sum_{j=k}^{d\log(1/|\epsilon|)}\frac{\hat{\mathrm{I}}_{j,\alpha}}{j^2}\right]\left[\sum_{i=k}^{d\log(1/|\epsilon|)}\frac{\hat{\mathrm{I}}_{i,\beta}}{i^2}\right]$$
$$+ \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} k^2\mathrm{I}_{\infty,\alpha}\left[\sum_{i=k}^{d\log(1/|\epsilon|)}\frac{\hat{I}_{i,\beta}}{i^2}\right] + \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} k^2\left[\sum_{j=k}^{d\log(1/|\epsilon|)}\frac{\hat{I}_{j,\alpha}}{j^2}\right]\mathrm{I}_{\infty,\beta}$$
$$+ \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} k^2 I_{\infty,\alpha}I_{\infty,\beta}$$
$$= \mathrm{I} + \mathrm{II} + \mathrm{II} + \mathrm{IV}\,.$$

Here II and III are symmetric. It suffices to estimate II.

We estimate IV first. Since $\sum k^2 \sim (\log(1/|\epsilon|))^3$, this is immediately small when multiplied with $\mathrm{I}_{\infty,\alpha}, \mathrm{I}_{\infty,\beta}$. For II, we get

$$\begin{aligned}
\mathrm{II} &= \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} k^2 \mathrm{I}_{\infty,\alpha}\Bigg[\sum_{i=k}^{d\log(1/|\epsilon|)} \frac{\hat{\mathrm{I}}_{i,\beta}}{i^2}\Bigg] \\
&< \mathrm{I}_{\infty,\alpha} \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} \Bigg[\sum_{i=k}^{d\log(1/|\epsilon|)} \hat{I}_{i,\beta}\Bigg] \\
&< \frac{1}{(\log(1/|\epsilon|))} \int \tilde{H}_\alpha(x)|x|^{1/\gamma-1}dx \int \tilde{H}_\beta(y)|y|^{1/\gamma-1}dy \to 0\,.
\end{aligned}$$

Finally we estimate I:

$$\begin{aligned}
\mathrm{I} &= \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} k^2 \Bigg[\sum_{j=k}^{d\log(1/|\epsilon|)} \frac{\hat{I}_{j,\alpha}}{j^2}\Bigg]\Bigg[\sum_{i=k}^{d\log(1/|\epsilon|)} \frac{\hat{I}_{i,\beta}}{i^2}\Bigg] \\
&< \sum_{k=\log 1/\delta}^{d\log(1/|\epsilon|)} \frac{1}{k^2}\Bigg[\sum_{j=k}^{d\log(1/|\epsilon|)} \hat{I}_{j,\alpha}\Bigg]\Bigg[\sum_{i=k}^{d\log(1/|\epsilon|)} \hat{I}_{i,\beta}\Bigg].
\end{aligned}$$

We can make this as small as we wish by choosing δ small.

26 Proof of Theorem 4

Proof. We use the approach in [FoS].

Let T be a positive harmonic current directed by $\mathcal{F}$. We want to show that $\int T \wedge T = 0$. Let $T_\epsilon = (\Phi_\epsilon)_* T$ and define T_ϵ^δ as the average of T_ϵ using a small neighborhood of identity in $U(3)$. Then since $T_\epsilon \rightharpoonup T$, we have $\int T \wedge T = \lim_{\epsilon\to 0} \int T \wedge T_\epsilon$. On the other hand $T_\epsilon^\delta = \omega + \partial S_\epsilon^\delta + \overline{\partial S}_\epsilon^\delta + i\partial\overline{\partial} u_\epsilon^\delta$ and $S_\epsilon^\delta \to S_\epsilon$ in L^2. So $\int T \wedge T_\epsilon = \lim_{|\delta|,|\delta'|\to 0, |\delta|,|\delta'|\ll \epsilon} \int T_\epsilon^\delta \wedge T^{\delta'}$. Hence as in [FoS] it is enough to show that

$$\lim_{\delta,\delta',\epsilon\to 0, |\delta|,|\delta'|\ll|\epsilon|} \int T_\epsilon^\delta \wedge T^{\delta'} = 0\,.$$

We can compute the geometric intersection $T_\epsilon^\delta \wedge T^{\delta'}$ and it is enough to estimate $T_\epsilon \wedge_g T$. Recall that if ϕ is a test function supported in B, then we define

$$\langle T_\epsilon \wedge_g T, \phi\rangle = \int \sum_{J_{\alpha,\beta}^\epsilon} \phi(p) H_\alpha(p) H_\beta^\epsilon(p) d\mu(\alpha) d\mu(\beta)\,.$$

where $J_{\alpha,\beta}^\epsilon$ consists of intersection points of Δ_α and Δ_β^ϵ. The following lemma is proved in [FoS].

Lemma 25. *We have that $\int T \wedge T_\epsilon = \int T \wedge_g T_\epsilon$. The same holds for $T^\delta, T_\epsilon^{\delta'}$*

$$\langle T_\epsilon \wedge_g T, \phi\rangle \le C\|\phi\|_\infty \int \sum_{J_{\alpha,\beta}^\epsilon} H_\alpha(p) H_\beta^\epsilon(p) d\mu(\alpha) d\mu(\beta)\,,$$

We know that the number of points in $J_{\alpha,\beta}^\epsilon$ is bounded by a fixed constant independent of ϵ. For p out of a fixed neighborhood of the singularities the integral converges to zero. This is the case considered in [FoS]. So it is enough to show that for $\delta > 0$ small enough

$$J_\epsilon(\delta) := \int \sum_{J^\epsilon_{\alpha,\beta}} H_\alpha(p) H^\epsilon_\beta(p) d\mu(\alpha) d\mu(\beta)$$

is arbitrarily small. This is precisely the content of Theorem 7, since all estimates are valid after composition by automorphisms in a small neighborhood of $U(3)$.

Consequently if T_1, T_2 are two such currents then $\int \frac{T_1+T_2}{2} \wedge \frac{T_1+T_2}{2} = 0$. Hence $\int T_1 \wedge T_2 = 0$, therefore T_1, T_2 are proportional. □

We give a dynamical consequence of the uniqueness of the harmonic current for $\mathcal{F} \in \mathcal{H}(d)$, here $\mathcal{H}(d)$ is the Zariski open set of foliations of degree d, introduced in Theorem 2. Recall from the introduction:

Corollary 3. *Let $\mathcal{F} \in \mathcal{H}(d)$. Let $\phi : \Delta \to L$ be the universal covering of a leaf L. Let $\tau_r := \frac{\phi_*[\log^+ \frac{r}{|z|} \Delta_r]}{\|\phi_*[\log^+ \frac{r}{|z|} \Delta_r]\|}$. Then $\lim_{r \to 1} \tau_r = T$, where T is the unique harmonic current directed by $\mathcal{F}$.*

Here Δ_r denotes the disc of center 0 and radius r. The corollary which is a consequence of paragraph 5 in [FoS] says that the normalized images of $\left[\log^+ \frac{r}{|z|} \Delta_r\right]$ converge to T. This is similar to the pointwise ergodic theorem, since we are averaging on an orbit.

Recall that the limit set of a leaf L is defined as $\lim(L) = \cap_n \overline{L \setminus K_n}$, where $K_n \subset K_{n+1}$ is an exhaustion of L by compact sets. One of the main questions in foliation theory is to describe the limit set of a foliation $\mathcal{F}$: $\lim(\mathcal{F}) := \overline{\cup_{L \in \mathcal{F}} \lim(L)}$. Corollary 3 implies in particular that for $\mathcal{F} \in \mathcal{H}(d)$, for every leaf $L \in \mathcal{F}$, $\lim(L)$ contains $\operatorname{supp}(T)$. Indeed as shown in [FoS],

$$\left\| \Phi_* \left[\log^+ \frac{r}{|z|} \Delta_r\right] \right\| \to \infty$$

as $r \to 1$. Hence $\operatorname{supp}(T) \subset \overline{L \setminus K_n}$ for every n.

Corollary 4. *The map $\lambda \to T_\lambda$ is continuous from $\mathcal{H}(d)$ with values in the positive harmonic currents of mass one. Let $\mathcal{F}_\lambda$ be a holomorphic family of foliations in $\mathcal{H}(d)$. Let (T_λ) be the associated currents. If a hyperbolic point $p_0 \in \operatorname{Supp}(T_{\lambda_0})$, then the perturbed hyperbolic point p_λ belongs to $\operatorname{Supp}(T_\lambda)$.*

Proof. Assume $\mathcal{F}_{\lambda_n} \to \mathcal{F}_{\lambda_0}$ in $\mathcal{H}(d)$. Let (T_{λ_n}) be the normalized positive harmonic currents associated to $\mathcal{F}_{\lambda_n}$. Since $\|T_{\lambda_n}\| = 1$, the sequence (T_{λ_n}) has cluster points. It is clear that any cluster point S is positive harmonic and directed by $\mathcal{F}_{\lambda_0}$. So $S = T_{\lambda_0}$ by uniqueness. Assume the support of T_{λ_0} intersects a ball $B(p_0, r)$ where p_0 is a hyperbolic singular point of $\mathcal{F}_{\lambda_0}$ and the ball is contained in the common domain of linearization of $p_\lambda \in \operatorname{Sing}(\mathcal{F}_\lambda), p_\lambda \to p_0$, p_λ hyperbolic.

From our local study of positive harmonic currents near a hyperbolic singular point $p_0 \in \operatorname{Supp}(T_{\lambda_0})$. Since $T_\lambda \to T_{\lambda_0}$, T_λ gives mass to $B(p_0, r)$, applying again the local study for T_λ we get that $p_\lambda \in \operatorname{Supp}(T_\lambda)$. □

Remark 2. Let f be a holomorphic endomorphism of $\mathbb{P}^2$. Let $\mathcal{F}$ be a foliation with only hyperbolic singularities. Then $f^*\mathcal{F}$ is a foliation and its singularities are not necessarily hyperbolic. However there is only one positive harmonic current of mass 1, directed by $f^*\mathcal{F}$. Indeed let T be any such current. We will show that $\int T \wedge T = 0$ which implies the uniqueness. Observe that f_*T is a current directed by $\mathcal{F}$. Hence $\int f_*T \wedge f_*T = 0$. Since f^* is a finite covering of degree d^2 we have

$$\int T \wedge T \le \int f^*[f_*T \wedge f_*T] = d^2 \int f_*T \wedge f_*T = 0\,.$$

27 Measure Associated to a Harmonic Current

Let $\mathcal{F} \in \mathcal{H}(d)$ be a holomorphic foliation as in Theorem 2. We know that there is a unique positive harmonic current T of mass one directed by $\mathcal{F}$.

We are going to associate to T a conformal, measurable metric along leaves that we will denote by g_T and also a positive finite measure μ_T which is related to the harmonic flow associated also to T. The metric g_T and the measure μ_T where first considered by S. Frankel, in the non-singular case [Fr] he proved in that case a version of Proposition 2 and Proposition 3.

On a flow box B disjoint from $E = \mathrm{Sing}(\mathcal{F})$, the current T can be written

$$T = \int h_\alpha [V_\alpha] d\mu(\alpha)$$

where h_α are positive harmonic functions and μ is a positive measure on a transversal A. The $[V_\alpha]$ are the currents of integration on plaques. On $B, \partial T = \tau \wedge T$ with $\tau = \partial h_\alpha / h_\alpha$, μ almost everywhere. Observe that τ is independent of the choice of h_α : if we replace h_α by $c_\alpha h_\alpha, c_\alpha \in \mathbb{R}^+$ then τ is unchanged.

We define the metric g_T on leaves by $g_T = \frac{i}{2} \tau \otimes \overline{\tau}$. Along the plaque V_α with a choice of coordinate (z_α) we have

$$g_T = \frac{i}{2} \left| \frac{\partial h_\alpha}{\partial z_\alpha} \right|^2 \frac{1}{h_\alpha^2} dz_\alpha \otimes d\overline{z}_\alpha \tag{1}$$

Define $\mathcal{C}_T = \{(\alpha, z); \frac{\partial h_\alpha}{\partial z}(\alpha, z) = 0\}$ it's the critical set of the "metric" g_T. We also define the current of bidegree $(2,2)$, μ_T, which we identify with a measure

$$\mu_T := i\tau \wedge \overline{\tau} \wedge T\,.$$

In local coordinates in a flow box B, we have

$$\mu_T = \int d\nu(\alpha) \int_{[V_\alpha]} \left| \frac{\partial h_\alpha}{\partial z_\alpha} \right|^2 \frac{1}{h_\alpha} (i dz_\alpha \wedge d\overline{z_\alpha})\,. \tag{2}$$

Proposition 2. *Let $\mathcal{F} \in \mathcal{H}(d)$. The metric g_T has constant negative curvature out of the set $\mathcal{C}_T$ where the metric vanishes.*

Proof. Since the current T is unique, every measurable set of leaves $\mathcal{A}$ has zero or full measure with respect to $\|T\|$. Define $\mathcal{N}_g := \{$leaves on which g_T vanishes identically$\}$. Since h_α is measurable, then $\mathcal{N}_g$ is measurable. So $\mathcal{N}_g$ is of zero or full measure. But if $\mathcal{N}_g$ is of full measure, $\partial T = 0$ and by conjugation $\overline{\partial} T = 0$, hence T is closed. A foliation $\mathcal{F}$ in $\mathcal{H}(d)$ admits no positive closed current directed by $\mathcal{F}$ since all singularities are hyperbolic. So $\mathcal{N}_g$ is of zero $\|T\|$ measure.

From (1) it is clear that the metric is conformal. On a flow box B, the curvature $\kappa(g)$ has the following expression out of C_T. The curvature is given by

$$\kappa(g) = -\frac{1}{4}\frac{\Delta \log g}{g} = \frac{1}{2}\frac{\Delta \log h_\alpha}{\left|\frac{\partial h_\alpha}{\partial z_\alpha}\right|^2 \frac{1}{h_\alpha^2}}\,.$$

So

$$\kappa(g_T) = \frac{h_\alpha^2}{|h_{\alpha,z}|^2}\left(\frac{\partial}{\partial \overline{z}}\left(\frac{h_{\alpha,z}}{h_\alpha}\right)\right).$$

Since h_α is harmonic we get $\kappa(g_T) = -1$. □

Because of the nature of the singularities, the leaves are uniformized by the unit disc Δ. Let g denote the Poincaré metric on leaves. We choose a normalization so that the curvature $\kappa(g)$ of g on leaves is -1.

Proposition 3. *Let T be the harmonic current associated to $\mathcal{F} \in \mathcal{H}(d)$. If g_T is the associated metric on leaves, then $g_T \leq g$.*

Proof. We have normalized the metric g_T so that on each leaf L_α, g_T has curvature -1 on $L_\alpha \setminus \mathcal{C}(T)$. Ahlfors' Schwarz lemma, applied to the abstract Riemann surface $L_\alpha \setminus \mathcal{C}_T$, implies that $g_T \leq g$. □

We will denote by $\Phi_\alpha : \Delta \to \mathcal{L}_\alpha$, the uniformizing map from Δ to $\mathcal{L}_\alpha$. When we fix a transversal A in a flow box we can choose for each $\alpha \in A$ a uniformizing map $\Phi_\alpha(0) = \alpha$, then Φ_α vary measurably. We will denote by Γ_α the group of deck transformations for the map Φ_α.

We want to define a vector field χ on $\mathcal{F}$ associated to the current T. The vector field will be defined as the metric g_T only $\|T\|$ a.e. On L_α, χ_α is collinear with the gradient field of h_α. We define χ_α on a flow box with local coordinates $z_\alpha = x_\alpha + iy_\alpha$ by

$$\chi_\alpha := c\frac{h_\alpha}{|h_z|^2}(h_{x_\alpha}, h_{y_\alpha})\,.$$

We choose the constant c so that $g_T(\chi_\alpha, \chi_\alpha) = 1$. The vector field χ_α is independent of the choice of h. It blows up at every point of $\mathcal{C}_T$. Which means that the integral curves of χ_α approach these points at infinite speed. So we have to take out these trajectories in order to have a well-defined flow. Observe that the set of these trajectories is of μ_T measure zero. It is clear that the integral curves of χ_α are along the level sets of the harmonic conjugates of h_α such that $f_\alpha = h_\alpha + iv_\alpha$ is holomorphic.

Theorem 9. *Let T be the positive harmonic current associated to $\mathcal{F} \in \mathcal{H}(d)$. Then the measure μ_T is finite. Moreover, if $\mathcal{F}_\lambda$ is a holomorphic family of foliations in $\mathcal{H}(d)$, $\lambda \in \Delta(\lambda_0, r)$, then the mass of μ_{T_λ} near hyperbolic singularities is uniformly small in a fixed neighborhood of the singularities.*

Proof. For a flow box B away from the singularities, it is clear that μ_T has finite mass. Indeed the functions h_α are positive harmonic, and by Harnack $h_\alpha/|\partial h_\alpha| \leq c$, hence μ_T has finite mass in B. It is enough to show that μ_T has finite mass in a flow box B_i near a hyperbolic singularity given by $\omega_0 = zdw - \lambda wdz$, $\lambda = a + ib$, $b \neq 0$. We use the parametrization

$$\psi_\alpha(\zeta) = \left(e^{i(\zeta + (\log|\alpha|)/b)}, \alpha e^{i\lambda(\zeta + (\log|\alpha|)/b)}\right)$$

by a sector near the hyperbolic singularity. Since $\psi_\alpha^* h_\alpha = H_\alpha$ is a positive harmonic function and μ a.e., $H_\alpha(\zeta) \to 0$ when $\Im\zeta \to +\infty$, then again by Harnack $\psi_\alpha^*(\tau)$ is bounded. The total mass of μ_T in B_i satisfies

$$\int_{B_i} \mu_T \leq \int_{D(w_0,r)\times S_\lambda} i\psi_\alpha^*(\tau) \wedge \psi_\alpha^*(\overline{\tau}) \wedge \psi_\alpha^*[V_\alpha] H_\alpha d\mu(\alpha)\,;$$

$\psi_\alpha^*[V_\alpha]$ is a graph in the flow box. It is of bounded area and $\int_{D(w_0,r)} H_\alpha d\mu(\alpha)$ defines a bounded harmonic function. So the mass μ_T is bounded near the origin.

Basically the slicing of μ_T along the leaves gives the area measure on leaves associated to the metric g_T. Let T_λ be the current associated to $\mathcal{F}_\lambda$, and let μ^λ denote the corresponding measure on a transversal. The linearizations associated to a holomorphically varying hyperbolic singularity vary holomorphically. Then $\int H_\alpha^\lambda d\mu^\lambda(\alpha) \to 0$ when $\Im\zeta \to +\infty$, uniformly when λ is near λ_0. (We don't say that H_α^λ vary holomorphically.) So the mass of μ_{T_λ} is uniformly small in a fixed neighborhood of the singularities if λ is close enough to λ_0. □

Theorem 10. *Let $\lambda \to \mathcal{F}_\lambda$ be a holomorphic family of foliations in $\mathcal{H}(d)$, parametrized by a disc Δ. Then $\lambda \to \mu_\lambda$ is a continuous family of measures.*

Proof. Let (T_λ) be the family of the positive harmonic currents directed by $\mathcal{F}_\lambda$. Recall that $\mu_{T_\lambda} = i\tau_\lambda \wedge \overline{\tau}_\lambda \wedge T_\lambda$.

Fix a flow box B for $\mathcal{F}_{\lambda_0}$ away from the singularities. We can consider (ϕ_λ) local biholomorphisms straightening $\mathcal{F}_\lambda$ in B, when $\lambda \to \lambda_0$. We know that the currents $S_\lambda := (\phi_\lambda)_* T_\lambda$ depend continuously on λ. We can write in B,

$$S_\lambda = \int [w = \alpha] h_\alpha^\lambda(z) d\mu_\lambda(\alpha)$$

where μ_λ is the measure on a fixed transversal $(z = z_0)$. We can assume that $h_\alpha^\lambda(z_0) = 1$ for all α, λ.

Since $S_\lambda \to S_{\lambda_0}$ then for every z we have $h_\alpha^\lambda(z)\mu_\lambda(\alpha) \to h_\alpha^{\lambda_0}\mu_{\lambda_0}(\alpha)$ weakly when $\lambda \to \lambda_0$.

The $(h_\alpha^\lambda)^2$ also vary slowly, by Harnack, so we also get that $\lambda \to (h_\alpha^\lambda(z))^2 \mu_\lambda(\alpha)$ is continuous for every z. Define

$$U_\lambda := \int [w = \alpha] (h_\alpha^\lambda)^2(z) d\mu_\lambda(\alpha)\,.$$

The family of positive currents U_λ is also continuous because $(h_\alpha^\lambda)^2$ is uniformly bounded. It follows that $\lambda \to i\partial\overline{\partial} U_\lambda$ is continuous, i.e.

$$\lambda \to \int |h_{\alpha,z}^\lambda|^2 [w = \alpha] d\mu_\lambda(\alpha)\,.$$

Using again Harnack inequalities for $1/h_\alpha^{\lambda^2}$, we find that $\lambda \to \mu_{T_\lambda}$ is continuous in B.

We have seen in Theorem 9 that μ_{T_λ} has uniformly small mass near the singularities. Hence $\lambda \to \mu_{T_\lambda}$ is continuous. □

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