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ON THE CUT LOCUS OF FREE, STEP TWO CARNOT GROUPS

LUCA RIZZI[‡] AND ULYSSE SERRES[‡]

ABSTRACT. In this note, we study the cut locus of the free, step two Carnot groups \mathbb{G}_k with k generators, equipped with their left-invariant Carnot-Carathéodory metric. In particular, we disprove the conjectures on the shape of the cut loci proposed in [Mya02, Mya06] and [MM16a], by exhibiting sets of cut points $C_k \subset \mathbb{G}_k$ which, for $k \geq 4$, are strictly larger than conjectured ones. While the latter were, respectively, smooth semi-algebraic sets of codimension $\Theta(k^2)$ and semi-algebraic sets of codimension $\Theta(k)$, the sets C_k are semi-algebraic and have codimension 2, yielding the best possible lower bound valid for all k on the size of the cut locus of \mathbb{G}_k .

Furthermore, we study the relation of the cut locus with the so-called abnormal set. In the low dimensional cases, it is known that

$$\text{Abn}_0(\mathbb{G}_k) = \overline{\text{Cut}_0(\mathbb{G}_k)} \setminus \text{Cut}_0(\mathbb{G}_k), \quad k = 2, 3.$$

For each $k \geq 4$, instead, we show that the cut locus always intersects the abnormal set, and there are plenty of abnormal geodesics with finite cut time.

Finally, and as a straightforward consequence of our results, we derive an explicit lower bound for the small time heat kernel asymptotics at the points of C_k .

The question whether C_k coincides with the cut locus for $k \geq 4$ remains open.

1. INTRODUCTION

We recall some basic facts about sub-Riemannian manifolds and their geodesics (see [ABB15, Rif14] for details). Let M be a smooth manifold and $\mathcal{D} \subset TM$ be a smooth distribution with constant rank $k = \text{rank } \mathcal{D}$, satisfying the Hörmander condition:

$$(1) \quad \text{Lie}(\Gamma(\mathcal{D}))_q = T_q M, \quad \forall q \in M,$$

where the l.h.s. denotes the smallest Lie algebra generated by smooth sections of \mathcal{D} . If g is a smooth scalar product defined on \mathcal{D} , then (\mathcal{D}, g) is a sub-Riemannian structure on M .

A Lipschitz path $\gamma : [0, T] \rightarrow M$ is *horizontal* if $\dot{\gamma}(t) \in \mathcal{D}_{\gamma(t)}$ for a.e. $t \in [0, T]$. For any horizontal path γ , we define its length as

$$(2) \quad L(\gamma) := \int_0^T \|\dot{\gamma}(t)\|_g dt.$$

Furthermore, we define the *sub-Riemannian distance* $d : M \times M \rightarrow \mathbb{R}$ as $d(q, q') := \inf L(\gamma)$, where the infimum is taken over all horizontal curves that join q with q' . Thanks to (1), d is finite and continuous, and so (M, d) is a locally compact length metric space.

A *geodesic* is a non-trivial horizontal curve that locally minimizes the length between its endpoints. The *cut time* of a geodesic $\gamma : [0, T] \rightarrow M$ is

$$(3) \quad t_{\text{cut}}(\gamma) := \sup\{t > 0 \mid \gamma|_{[0, t]} \text{ is a minimizing geodesic}\} > 0.$$

Assuming that (M, d) is complete, the *cut locus* of $q \in M$ is the set of *cut points* $\gamma(t_{\text{cut}}(\gamma))$:

$$(4) \quad \text{Cut}_q := \{\gamma(t_{\text{cut}}(\gamma)) \mid \gamma \text{ is a geodesic starting at } q\}.$$

The cut locus, together with the so-called abnormal geodesics, play an important role in the regularity properties of the sub-Riemannian distance [CR08, RT09, Agr09, Agr16, MM16b] and of the heat kernel of sub-Laplacians [BBN12, BBCN16, BBN16]. Its properties are quite different with respect to the Riemannian setting, for example, q is an accumulation

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point for Cut_q , and $\text{Cut}_q \cup \{q\}$ is not closed in general. Moreover, while in Riemannian geometry $q' \in \text{Cut}_q$ if and only if q' is a critical value of the exponential map or there are two distinct minimizing geodesics joining q with q' , this characterization is no longer true in the sub-Riemannian case due to the occurrence of abnormal geodesics.

The cut time is known explicitly for a handful of left-invariant structures on 3D Lie groups [BR08, Sac11, BSB16], on some Stiefel manifolds [AM14], and for the following non-disjoint classes of Carnot groups: contact [ABB12], corank 1 [Riz16], corank 2 [BBG12], the Engel group [AS15], the bi-Heisenberg groups [BBN16] (that is, corank 1 Carnot groups of dimension 5), and H -type groups [AM16]. From the knowledge of the cut time, the cut locus can be computed via (4). In a few symmetric cases, this yields an elegant and compact description for the cut locus.

1.1. Summary of the results. In this paper, we focus on the hierarchy \mathbb{G}_k of *free, step 2 Carnot groups of rank $k \geq 2$* . Their first appearance traces back to the seminal works of Gaveau [Gav77] and Brockett [Bro82], and for this reason the corresponding minimization problem is called the *Gaveau-Brockett problem* by Liu and Sussmann [LS95].

The groups \mathbb{G}_k have the largest sets of symmetries among all Carnot groups of the same rank and step, and their geodesics can be computed quite explicitly. These features lead to expect the existence of an explicit formula describing their cut locus. This is indeed the case for $k = 2$ (the Heisenberg group), where the cut locus is described succinctly as the zero set of an algebraic function. Surprisingly, such an algebraic description also exists for the free step 2 Carnot group of rank 3 – the so-called (3, 6) group – as proven independently and with different strategies in [Mya02] and [MM16a].

Extrapolating from the known results in these cases, in [Mya02, Mya06, MM16a], the authors conjectured precise algebraic formulas for the cut loci of \mathbb{G}_k , for all $k \geq 2$. In this note, we disprove these conjectures. In particular, we exhibit an explicit hierarchy of sets $C_k \subset \mathbb{G}_k$ of cut points (see Definition 5), which coincide with the corresponding cut loci for $k = 2, 3$, but are strictly larger than the conjectured ones for $k \geq 4$. While the previously conjectured cut loci were, respectively, smooth algebraic sets of codimension $\Theta(k^2)$ [Mya02, Mya06] and algebraic sets of codimension $\Theta(k)$ [MM16a], the set C_k is semi-algebraic of codimension 2, which is the best possible lower bound valid for all k on the size of the cut loci (see Theorem 11).

Furthermore, we study the relation between the cut locus and the so-called abnormal set. In the low dimensional cases, it is known that

$$(5) \quad \text{Abn}_0(\mathbb{G}_k) = \overline{\text{Cut}_0(\mathbb{G}_k)} \setminus \text{Cut}_0(\mathbb{G}_k), \quad k = 2, 3.$$

Instead, for each $k \geq 4$, we show that the cut locus always intersects the abnormal set, and that there are plenty of abnormal geodesics with finite cut time (see Proposition 12).

Finally, and as a straightforward consequence of our results, we obtain an explicit lower bound for the small time heat kernel asymptotics at the points of C_k (see Theorem 13).

2. FREE STEP 2 CARNOT GROUPS OF RANK k

We refer to [Mon02, Jea14], for the definition of Carnot group. Here, we only deal with the specific free, step 2 case. Let $\mathbb{G}_k := \mathbb{R}^k \oplus \wedge^2 \mathbb{R}^k$. We identify $\wedge^2 \mathbb{R}^k$ with the vector space of skew-symmetric real matrices, that is $v \wedge w = vw^* - wv^*$ for $v, w \in \mathbb{R}^k$. We denote points $(x, Y) \in \mathbb{G}_k$, where $x \in \mathbb{R}^k$ and Y is a skew-symmetric matrix. The free, step 2 Carnot group of rank k is the sub-Riemannian structure on \mathbb{G}_k generated by the set of global orthonormal vector fields:

$$(6) \quad X_i := \partial_{x_i} - \frac{1}{2} \sum_{1 \leq \ell < m \leq k} (e_i \wedge x)_{\ell m} \partial_{Y_{\ell m}}, \quad i = 1, \dots, k,$$

where $\{e_1, \dots, e_n\}$ is the standard basis of \mathbb{R}^k . More precisely, the horizontal distribution is defined by $\mathcal{D} := \text{span}\{X_1, \dots, X_k\}$ and the sub-Riemannian metric by $g(X_i, X_j) = \delta_{ij}$.

For all $i < j$, we have $[X_i, X_j] = \partial_{Y_{ij}}$. In particular, the vector fields (6) generate the free, nilpotent Lie algebra of step 2 with k generators:

$$(7) \quad \mathfrak{g} = \mathfrak{g}_1 \oplus \mathfrak{g}_2, \quad \text{where} \quad \mathfrak{g}_1 = \text{span}\{X_1, \dots, X_k\}, \quad \mathfrak{g}_2 = \text{span}\{\partial_{Y_{ij}}\}_{i < j}.$$

There exists a unique Lie group structure on \mathbb{G}_k such that the vector fields X_i are left-invariant, given by the polynomial product law

$$(8) \quad (x, Y) \star (x', Y') = \left(x + x', Y + Y' + \frac{1}{2}x \wedge x' \right).$$

Thus, (\mathbb{G}_k, \star) is a connected, simply connected Lie group of dimension $k(k+1)/2$, such that its Lie algebra \mathfrak{g} of left-invariant vector fields is isomorphic to the free, nilpotent, stratified Lie algebra of step 2 with k generators, and such that the first stratum \mathfrak{g}_1 is equipped with a left-invariant scalar product. Any Lie group (\mathbb{G}'_k, \star') with the same properties is homomorphic to (\mathbb{G}_k, \star) and they carry isometric sub-Riemannian structures.

Carnot groups are equipped with a one-parameter family of dilations. For \mathbb{G}_k , it is given by $\delta_\varepsilon(x, Y) := (\varepsilon x, \varepsilon^2 Y)$, for $\varepsilon > 0$. As a consequence of this fact, the metric space (\mathbb{G}_k, d) are complete, and there exists a minimizing geodesic joining any given pair of points.

Example 1. The case $k = 2$ is the well-known Heisenberg group. Indeed, we can identify $(x, Y) \in \mathbb{R}^2 \oplus \wedge^2 \mathbb{R}^2$ with $(x, z) \in \mathbb{R}^2 \oplus \mathbb{R}$, so that the generating vector fields (6) read

$$(9) \quad X_1 = \partial_{x_1} - \frac{x_2}{2} \partial_z, \quad X_2 = \partial_{x_2} + \frac{x_1}{2} \partial_z.$$

Example 2. The case $k = 3$ can be dealt with by identifying $(x, Y) \in \mathbb{R}^3 \oplus \wedge^2 \mathbb{R}^3$ with $(x, t) \in \mathbb{R}^3 \oplus \mathbb{R}^3$. More precisely, any 3×3 skew-symmetric matrix can be written as $Y = v \wedge w$ (in a non-unique way), and is identified with the cross product $t = v \times w$. Under this identification, the tautological action of Y on \mathbb{R}^3 reads

$$(10) \quad Yx = (v \wedge w)x = x \times (v \times w) = x \times t, \quad \forall x \in \mathbb{R}^3,$$

and the generating vector fields (6) are

$$(11) \quad X_1 = \partial_{x_1} + \frac{x_3}{2} \partial_{t_2} - \frac{x_2}{2} \partial_{t_3}, \quad X_2 = \partial_{x_2} + \frac{x_1}{2} \partial_{t_3} - \frac{x_3}{2} \partial_{t_1}, \quad X_3 = \partial_{x_3} + \frac{x_2}{2} \partial_{t_1} - \frac{x_1}{2} \partial_{t_2}.$$

2.1. Geodesics. In this case, a Lipschitz path $\gamma : [0, T] \rightarrow \mathbb{G}_k$ is horizontal if there is a control $u \in L^\infty([0, T], \mathbb{R}^k)$ such that, for almost every $t \in [0, T]$, we have

$$(12) \quad \dot{\gamma}(t) = \sum_{i=1}^k u_i(t) X_i(\gamma(t)).$$

The standard method to solve the length minimization problem is based on the Pontryagin maximum principle. In the step 2 case, thanks to Goh condition, one can rule out all the so-called strictly abnormal curves. This analysis (see e.g. [LS95, Appendix A]) yields that geodesics are all the horizontal curves $\gamma(t) = (x(t), Y(t))$ with control

$$(13) \quad u(t) = e^{-t\Omega} p, \quad (p, \Omega) \in \mathbb{R}^k \oplus \wedge^2 \mathbb{R}^k.$$

In particular, all geodesics are real-analytic curves. The pair (p, Ω) is also referred to as the *initial covector* in the Hamiltonian formalism. Taking into account the explicit fields (6), for any fixed (p, Ω) , the actual geodesic can be recovered integrating

$$(14) \quad \dot{x}(t) = u(t), \quad \dot{Y}(t) = \frac{1}{2}x(t) \wedge u(t).$$

Remark 3. We point out a useful observation from [GJZ09, Prop. 3], which follows by putting Ω in real normal form. For any control $u(t)$ as in (13), there is a unique $\tilde{\Omega} \in \wedge^2 \mathbb{R}^k$ with all simple non-zero eigenvalues and largest possible kernel such that $e^{-t\Omega} p = e^{-t\tilde{\Omega}} p$.

Most of the progress in the study of free Carnot groups of low dimension ($k = 2, 3$) is due to the fact that (14) can be explicitly integrated in terms of trigonometric functions. Geodesics for the case $k = 2$, corresponding to the Heisenberg group, are well known. For the case $k = 3$, explicit formulas appeared first in [Mya02]. An explicit integration of the geodesic flow for the general case \mathbb{G}_k appeared first in [Mya06, Thm. 4.1]. However, if the latter were correct, it would imply that the geodesic flow can only reach points (x, Y) with $\text{rank}(Y) = 2$. To our best knowledge, the only complete and correct integration of the geodesic flow for general \mathbb{G}_k appears in [MPAM06], in terms of the spectral projectors of Ω , together with explicit worked out examples for all $k \leq 5$.

3. THE CONJECTURED CUT LOCI

By the left-invariance of the sub-Riemannian structure on \mathbb{G}_k , one can recover $\text{Cut}_q(\mathbb{G}_k)$ for any $q \in \mathbb{G}_k$ by left translation of $\text{Cut}_0(\mathbb{G}_k)$, where $0 = (0, 0)$ is the identity of \mathbb{G}_k . In the following, with the term ‘‘cut locus’’, we will refer to $\text{Cut}_0(\mathbb{G}_k)$.

The cut locus of \mathbb{G}_2 (the Heisenberg group) is well known, and consists in the set of points $(0, Y) \in \mathbb{R}^2 \oplus \wedge^2 \mathbb{R}^2$, with $Y \neq 0$. The computation of the cut time and cut locus for the case $k = 3$ is much harder, and requires a careful manipulation of geodesic equations and symmetries. This has been done independently in [Mya02] and [MM16a]. There, it was proved that, for the step 2 free Carnot groups of rank $k = 2, 3$, one has

$$(15) \quad \text{Cut}_0(\mathbb{G}_k) = \{(x, Y) \mid Y = v \wedge w \neq 0, Yx = 0\}, \quad k = 2, 3.$$

The characterization in (15) being dimension-free, the authors were naturally led to two closely related conjectures.

Conjecture 1 ([Mya02, Mya06]). *The cut locus of step 2, free Carnot group of rank k is*

$$(16) \quad P_k := \{(x, Y) \mid Y = v \wedge w \neq 0, Yx = 0\}.$$

Conjecture 2 ([MM16a]). *The cut locus of step 2, free Carnot group of rank k is*

$$(17) \quad \Sigma_k := \{(x, Y) \mid Y \neq 0, Yx = 0\}.$$

Clearly, $\Sigma_k = P_k$ for $k = 2, 3$, but $P_k \subsetneq \Sigma_k$ for $k \geq 4$. These conjectures imply analogous claims on the size of the cut loci, in particular $\text{codim}(P_k) = \Theta(k^2)$ and $\text{codim}(\Sigma_k) = \Theta(k)$, for large k (see the forthcoming Proposition 4).

3.1. Semi-algebraic sets. A set $A \subset \mathbb{R}^n$ is *semi-algebraic* if it is the result of a finite number of unions and intersections of sets of the form $\{f = 0\}$, $\{g > 0\}$, where f, g are polynomials on \mathbb{R}^n . We recall some of their basic properties, referring to [BCR98] for details. If A is smooth, its dimension as a semi-algebraic set [BCR98, Def. 2.8.1] is equal to its dimension as a smooth manifold. Moreover, if A is the finite union of semi-algebraic sets A_1, \dots, A_p , then $\dim(A) = \max_i \dim(A_i)$. Finally, if A is a semi-algebraic set, then its closure, its interior and any Cartesian projection of A are semi-algebraic sets.

Proposition 4. *$P_k \subseteq \mathbb{G}_k$ is a smooth semi-algebraic set of codimension $(k^2 - 5k + 10)/2$. $\Sigma_k \subseteq \mathbb{G}_k$ is a semi-algebraic set of codimension $2\lfloor k/2 \rfloor$.*

Proof. It is clear that both sets are semi-algebraic. Notice also that

$$(18) \quad \Sigma_k = \bigsqcup_{r=1}^{\lfloor k/2 \rfloor} \Sigma_k^{2r}, \quad \Sigma_k^{2r} = \{(x, Y) \mid Yx = 0, \text{rank}(Y) = 2r\}.$$

Indeed $P_k = \Sigma_k^2$. We now prove that each Σ_k^{2r} is a smooth manifold and we compute its codimension. The set $S_{2r} \subset \wedge^2 \mathbb{R}^k$ of rank $2r$ skew-symmetric matrices is a smooth submanifold of codimension $\dim(\mathfrak{so}(k-2r)) = (k-2r)(k-2r-1)/2$. Let $\phi_{2r} : \mathbb{R}^k \times S_{2r} \rightarrow \mathbb{R}^k$ be the smooth map $\phi_{2r}(x, Y) = Yx$. Then, $\Sigma_k^{2r} = \phi_{2r}^{-1}(0)$.

We claim that ϕ_{2r} has rank $2r$. This claim concludes the proof since $\phi_{2r}^{-1}(0)$ is then a codimension $2r$ submanifold of a codimension $(k-2r)(k-2r-1)/2$ submanifold of \mathbb{G}_k , that is a submanifold of codimension $(k-2r)(k-2r-1)/2+2r = (k^2 - (4r+1)k + 2r(2r+3))/2$. To prove the claim, we drop the subscript from the notation ϕ_{2r} , and we assume, without loss of generality, that $(x, Y) \in \Sigma_k^{2r}$ is of the form

$$(19) \quad Y = \begin{pmatrix} \bar{Y} \\ \mathbb{0}_{k-2r} \end{pmatrix}, \quad x = \begin{pmatrix} 0 \\ x_0 \end{pmatrix}, \quad \text{rank}(\bar{Y}) = 2r, \quad x_0 \in \mathbb{R}^{k-2r}.$$

The smooth variations $\gamma_i(\varepsilon) = (x + \varepsilon e_i, Y) \in \mathbb{R}^k \times S_{2r}$, for $i = 1, \dots, 2r$, are such that

$$(20) \quad \partial_t \phi(\gamma_i)(0) = \bar{Y} e_i.$$

Thus, the image of the differential of ϕ at (x, Y) contains $\text{span}\{e_1, \dots, e_{2r}\}$, and $\text{rank}(\phi) \geq 2r$. Suppose that $\text{rank}(\phi) > 2r$. Therefore, there exists $\gamma(t) = (x + tx', Y + tY') \in \mathbb{R}^k \times S_{2r}$, such that $\partial_t \phi(\gamma(0))$ and $\text{span}\{e_1, \dots, e_{2r}\}$ are independent. Splitting Y' as in (19),

$$(21) \quad Y' = \begin{pmatrix} Y'_1 & Y'_2 \\ Y'_3 & Y'_4 \end{pmatrix}, \quad \text{we obtain} \quad \partial_t \phi(\gamma(0)) = \begin{pmatrix} * \\ Y'_4 x_0 \end{pmatrix},$$

where the latter is independent of $\text{span}\{e_1, \dots, e_{2r}\}$. But this means that, for sufficiently small t , we have $\text{rank}(Y + tY') > 2r$, which contradicts the fact that $\gamma \in \mathbb{R}^k \times S_{2r}$. \square

4. A LARGER SET OF CUT POINTS

The orthogonal group $O(k)$ acts smoothly on \mathbb{G}_k . In particular, any $M \in O(k)$ induces an isometry of Carnot groups $\rho_M : \mathbb{G}_k \rightarrow \mathbb{G}_k$, given by $\rho_M(x, Y) = (Mx, MYM^*)$.

Definition 5. We define C_k as the set of points $(x, Y) \in \mathbb{R}^k \oplus \wedge^2 \mathbb{R}^k$, with $Y \neq 0$, such that there exists a non-trivial $M \in O(k)$ stabilizing (x, Y) , i.e.

$$(22) \quad Mx = x, \quad MYM^* = Y,$$

and such that $M|_{\ker Y} = \mathbb{1}$.

For the Heisenberg group, $C_2 = \Sigma_2 = P_2 = \{(0, Y) \mid Y \neq 0\}$. For rank $k = 3$, we can write $Y = v \wedge w$ for some (non-unique) pair $v, w \in \mathbb{R}^k$. In this case, any $M \in O(3)$ such that $MYM^* = Y$ is an orthogonal transformation in the plane $\text{span}\{v, w\} = (\ker Y)^\perp$. By the last condition, such a rotation is non-trivial. Thus, the condition $Mx = x$ implies that $x \perp \text{span}\{v, w\}$, and $C_3 = \Sigma_3 = P_3$. As it will be evident from the forthcoming discussion about normal forms, this is no longer true for $k \geq 4$. We now clarify the shape of C_k .

4.1. Normal forms. Let $(x, Y) \in \mathbb{G}_k$. Let $0 < \alpha_1 < \dots < \alpha_\ell$ be the absolute values of the non-zero distinct eigenvalues of Y , each having multiplicity m_i , and $m_0 = \dim(\ker Y)$. Up to an isometry ρ_O , we can assume that Y has the real normal form

$$(23) \quad Y = \begin{pmatrix} \alpha_1 \mathbb{J}_{2m_1} & & & \\ & \ddots & & \\ & & \alpha_\ell \mathbb{J}_{2m_\ell} & \\ & & & \mathbb{0}_{m_0} \end{pmatrix}, \quad \mathbb{J}_{2m} = \begin{pmatrix} 0 & \mathbb{1}_m \\ -\mathbb{1}_m & 0 \end{pmatrix}.$$

Accordingly, we write $x = (x_1, \dots, x_\ell, x_0)$, with $x_i \in \mathbb{R}^{2m_i}$ for $i = 1, \dots, \ell$, and $x_0 \in \mathbb{R}^{m_0}$.

If we insist that $(x, Y) \in C_k$, the conditions $M|_{\ker Y} = \mathbb{1}$ and $MYM^* = Y$ imply that

$$(24) \quad M = \begin{pmatrix} M_1 & & & \\ & \ddots & & \\ & & M_\ell & \\ & & & \mathbb{1}_{m_0} \end{pmatrix}, \quad M_i \in O(2m_i) \cap \text{Sp}(2m_i) \simeq \text{U}(m_i).$$

Thus, the conditions $Mx = x$, and $M \neq \mathbb{1}$ yield that $(x, Y) \in C_k$ if and only if, for some $i \in \{1, \dots, \ell\}$, either $x_i = 0$ or $m_i > 1$. In the first case, there is no further restriction on M_i , while in the second we must have $M_i x_i = x_i$. Thus, if $(x, Y) \in C_k$, the set

$$(25) \quad \mathcal{M}(x, Y) := \{M \in \mathrm{O}(k) \text{ satisfying the property of Definition 5}\} \cup \{\mathbb{1}_k\},$$

is a non-trivial Lie subgroup of $\mathrm{O}(k)$ of dimension

$$(26) \quad \dim \mathcal{M}(x, Y) = \sum_{i \in I_0} \dim \mathrm{U}(m_i) + \sum_{i \notin I_0} \dim \mathrm{U}(m_i - 1),$$

where $I_0 \subseteq \{1, \dots, \ell\}$ is the set of indices i such that $x_i = 0$. With this notation, we have the following.

Proposition 6. *For any geodesic γ joining the origin with $(x, Y) \in C_k$, there exists a family of mutually distinct geodesics with the same endpoints and length, obtained by the action of ρ_M on γ , with $M \in \mathcal{M}(x, Y)$. The dimension of such a family is*

$$(27) \quad N(x, Y) = \sum_{i \in I_0} m_i^2 + \sum_{i \notin I_0} (m_i - 1)^2.$$

Proof. For all $M \in \mathcal{M}(x, Y)$, the curves $\rho_M(\gamma)$ are geodesics joining the same endpoints and with the same length of γ . By contradiction, assume that $\rho_{M_1}(\gamma(t)) = \rho_{M_2}(\gamma(t))$ for all $t \in [0, T]$ and for $M_1 \neq M_2 \in \mathcal{M}(x, Y)$. In particular, $\mathbb{1} \neq M_2^* M_1 \in \mathcal{M}(x, Y)$. Let $E \subsetneq \mathbb{R}^n$ be the eigenspace of $M_2^* M_1$ corresponding to the eigenvalue 1. Since $M_1 x(t) = M_2 x(t)$, and $\dot{x}(t) = u(t)$, both $u(t), x(t) \in E$ for all $t \in [0, 1]$. The geodesic equations (14) imply

$$(28) \quad Y(t) \in \wedge^2 E \subsetneq \wedge^2 \mathbb{R}^k.$$

Let $v \perp E$, with $v \neq 0$. By (28), $v \in \ker Y$. By Definition 5, however, $M_2^* M_1 v = v$, hence $v \in E$ and $v = 0$. This is a contradiction, so the $\rho_M(\gamma)$ are mutually distinct. The dimension of such a family is $N(x, Y) = \dim \mathcal{M}(x, Y)$ given by (26). \square

Remark 7. By construction, the family in Proposition 6 is certainly composed of distinct geodesics obtained from a given one by isometric transformations. This might not exhaust all geodesics joining the origin with a given point $(x, Y) \in C_k$. For example, in corank 1 Carnot groups there are continuous families of non-isometric geodesics joining the origin with a given (non-generic) point, all having the same length [LR14].

Proposition 8. *For all $k \geq 2$, the set $C_k \subset \mathbb{G}_k$ is semi-algebraic of codimension 2.*

Proof. By Definition 5, $(x, Y) \in C_k$ if and only if there exist $M \in \mathrm{O}(k)$ stabilizing (x, Y) , a matrix $W \in \mathbb{R}^{k \times k}$ whose columns generate $\ker Y$, and $M|_{\ker Y} = \mathbb{1}$, that is $MW = W$. Thus, C_k is the projection on the first two factors of the set $V_k \subset \mathbb{R}^k \times \wedge^2 \mathbb{R}^k \times \mathrm{O}(k) \times \mathbb{R}^{k \times k}$, defined by the following formula:

$$(29) \quad V_k := \{(x, Y, M, W) \mid Mx = x, \quad MYM^* = Y, \\ \text{rank}(W) = k - \text{rank}(Y), \quad YW = 0, \quad MW = W\}.$$

The rank conditions being semi-algebraic, V_k is a semi-algebraic set, and so is C_k .

To compute the dimension of C_k , we follow a strategy inspired by [AGL15, App. A]. We decompose C_k as the disjoint union of a finite number of smooth semi-algebraic sets, each one containing points (x, Y) with the same ‘‘type’’ of normal form as in Section 4.1:

$$(30) \quad C_k = \bigsqcup_{r=1}^{\lfloor k/2 \rfloor} \left(\bigsqcup_{\ell=1}^{r-1} \bigsqcup_{m_1 + \dots + m_\ell = r} C_k^{2r|m_1, \dots, m_\ell} \bigsqcup_{I_0 \neq \emptyset} C_k^{2r|1, \dots, 1|I_0} \right).$$

Each component in (30) is labeled by the rank $2r$ of Y , and the multiplicities m_1, \dots, m_ℓ of its non-zero distinct eigenvalues, ordered according to their absolute values $0 < \alpha_1 < \dots < \alpha_\ell$. In the special case of all simple eigenvalues $\ell = r$, that is $m_1 = \dots = m_r = 1$,

we further decompose according to the set $I_0 \subseteq \{1, \dots, r\}$ such that $x_i = 0$ for $i \in I_0$, and $x_i \neq 0$ for $i \notin I_0$. According to Section 4.1, this decomposition exhausts all points of C_k .

We now prove that the component $C_k^{2r|1, \dots, 1|I_0}$, corresponding to the case in which $\text{rank}(Y) = 2r = 2\lfloor k/2 \rfloor$ is maximal, with simple eigenvalues, and where $I_0 = \{i\}$ is a singleton, is smooth of codimension 2. A similar argument, which we omit, proves that all the other components in the decomposition are smooth, and with larger codimension.

Assume, for simplicity, that k is even and that $I_0 = \{1\}$. Let $\mathbb{R}_*^n = \mathbb{R}^n \setminus \{0\}$ and $\mathbb{R}_{\text{ord}}^n$ denote the open subset of ordered, distinct n -tuples $0 < \alpha_1 < \dots < \alpha_n$. Consider the map $\Phi : \mathbb{R}_{\text{ord}}^{k/2} \times \mathbb{R}_*^{k/2-1} \times \text{O}(k)/\text{U}(1) \rightarrow C_k^{2k|1, \dots, 1|I_0}$ given by

$$(31) \quad \Phi(\alpha_1, \dots, \alpha_{k/2}, b_2, \dots, b_{k/2}, M) = \rho_M \left(\begin{pmatrix} 0 \\ b_2 \\ \vdots \\ b_{k/2} \end{pmatrix}, \begin{pmatrix} \alpha_1 \mathbb{J}_2 & & & \\ & \alpha_2 \mathbb{J}_2 & & \\ & & \ddots & \\ & & & \alpha_{k/2} \mathbb{J}_2 \end{pmatrix} \right),$$

where $\text{O}(k)/\text{U}(1)$ is the homogeneous space (a smooth manifold) of left cosets MU , where $U \in \text{U}(1) \subset \text{O}(k)$ is the subgroup that stabilizes the given normal form of (x, Y) , that is

$$(32) \quad U = \begin{pmatrix} M_1 & & & \\ & \mathbb{1}_2 & & \\ & & \ddots & \\ & & & \mathbb{1}_2 \end{pmatrix}, \quad M_1 \in \text{O}(2) \cup \text{Sp}(2) \simeq \text{U}(1).$$

The map Φ is a bijection. This gives $C_k^{2k|1, \dots, 1|I_0}$ a smooth structure, with dimension

$$(33) \quad \frac{k}{2} + \left(\frac{k}{2} - 1 \right) + \dim \text{O}(k)/\text{U}(1) = \frac{k(k+1)}{2} - 2.$$

The same argument yields the same formula for odd k . Thus, since $\dim(\mathbb{G}_k) = k(k+1)/2$, the codimension of the larger component of C_k is 2. Notice that, for $k = 2, 3$, there is only one component in (30), hence in these cases C_k is a *smooth* semi-algebraic set. \square

The next statement holds true, in particular, for all step 2 Carnot groups.

Lemma 9. *Let (\mathcal{D}, g) be a complete sub-Riemannian structure on M . Assume that all minimizing curves are real-analytic. If there exist two distinct minimizing geodesics joining q with q' , then $q' \in \text{Cut}_q$.*

Proof. Let $\gamma_i : [0, T] \rightarrow M$, $i = 1, 2$, be two distinct geodesics joining q with q' . In local coordinates, there exists $n \in \mathbb{N}$ such that their n -th derivatives at T are different. Assume that we can extend γ_1 to a minimizing geodesic on the interval $[0, T + \varepsilon]$, with $\varepsilon > 0$. Then, the curve $\gamma : [0, T + \varepsilon] \rightarrow M$ such that $\gamma|_{[0, T]} = \gamma_2$, and $\gamma|_{[T, T + \varepsilon]} = \gamma_1$ is minimizing on the interval $[0, T + \varepsilon]$, but it is not real-analytic. This is a contradiction, then $q' \in \text{Cut}_q$. \square

Remark 10. The conclusion of Lemma 9 holds, although with a different proof, replacing the real-analytic hypothesis with the assumption that there are no abnormal minimizing curves. Otherwise, one cannot a priori exclude the case of ‘‘branching’’ minimizing curves.

It is now clear that the set C_k of Definition 5 is a set of cut points, which for $k \geq 4$ is strictly larger than the sets P_k and Σ_k of Conjectures 1 and 2.

Theorem 11. *The following chain of inclusions holds true, for all $k \geq 4$:*

$$(34) \quad P_k \subsetneq \Sigma_k \subsetneq C_k \subseteq \text{Cut}_0(\mathbb{G}_k).$$

In particular, if $\text{Cut}_0(\mathbb{G}_k)$ is semi-algebraic, $\text{codim}(\text{Cut}_0(\mathbb{G}_k)) \leq 2$, for all k .

Proof. The first strict inclusion is trivial. The second is a consequence of the normal forms in Section 4.1. The third inclusion follows from Proposition 6, applied to minimizing geodesics, and Lemma 9. The claim on the codimension follows from Proposition 8. \square

4.2. Relation with the abnormal set. Let $\text{End} : L^\infty([0, 1], \mathbb{R}^k) \rightarrow \mathbb{G}_k$ be the *end-point map*, which associates with a given control $u(t)$ the end-point of the corresponding horizontal curve (12). Trajectories corresponding to critical points of End are called *singular curves*, and the set $\text{Abn}_0(\mathbb{G}_k)$ of critical values of End is the so-called *abnormal set*. Determining the “size” of $\text{Abn}_0(\mathbb{G}_k)$ on a general sub-Riemannian manifold is one of the hard open problems in the field [Agr14]. A computation using the formula for the differential of the end-point map and the chronological calculus (see [ABB15]) yields

$$(35) \quad \text{Abn}_0(\mathbb{G}_k) = \bigsqcup_{W \in \text{Gr}(k, k-2)} W \oplus \wedge^2 W, \quad \forall k \geq 2,$$

where $\text{Gr}(k, k-2)$ is the Grassmannian of codimension 2 subspaces of \mathbb{R}^k . We refer to [DMO⁺15] for a proof of (35) not resorting to chronological calculus, and several alternative characterizations. We point out that, if $\dim(\ker Y) \geq 3$, then $(x, Y) \in \text{Abn}_0(\mathbb{G}_k)$.

In the low dimensional cases, it turns out that the boundary of the cut locus coincides with the abnormal set:

$$(36) \quad \text{Abn}_0(\mathbb{G}_k) = \overline{\text{Cut}_0(\mathbb{G}_k)} \setminus \text{Cut}_0(\mathbb{G}_k), \quad k = 2, 3.$$

For $k \geq 4$, formula (36) is no longer true. More precisely, we have the following result, yielding also the first example of abnormal geodesic with finite cut time.

Proposition 12. *For all $k \geq 2$, we have*

$$(37) \quad \overline{C}_k \setminus C_k \subseteq \text{Abn}_0(\mathbb{G}_k) \subsetneq \overline{C}_k.$$

For each $k \geq 4$, the first inclusion is strict, and thus $\text{Cut}_0(\mathbb{G}_k) \cap \text{Abn}_0(\mathbb{G}_k) \neq \emptyset$. Moreover, there exist abnormal geodesics with finite cut time.

Proof. Let $(x, Y) \in \overline{C}_k \setminus C_k$. By the discussion in Section 4.1, we assume that

$$(38) \quad x = \begin{pmatrix} x_1 \\ \vdots \\ x_\ell \\ x_0 \end{pmatrix}, \quad Y = \begin{pmatrix} \alpha_1 \mathbb{J}_2 & & & & \\ & \ddots & & & \\ & & \alpha_\ell \mathbb{J}_2 & & \\ & & & & \mathbb{0}_{m_0} \end{pmatrix}, \quad 0 \neq x_i \in \mathbb{R}^2, \quad i = 1, \dots, \ell.$$

Let $(x^n, Y^n) \in C_k$ be a sequence converging to (x, Y) as $n \rightarrow +\infty$. Since the non-zero eigenvalues of Y are simple, the same holds for the non-zero eigenvalues of Y^n . Consequently, the associated real projectors π_i^n , for $i = 1, \dots, \ell$, are continuous [Kat95, Chap. 2, Thm. 5.1], and so are the projections $\pi_\perp^n := \mathbb{1} - \sum_{i=1}^\ell \pi_i^n$. Observe that $\lim_n \pi_\perp^n = \pi_0$ is the projection on $\ker Y$, but π_\perp^n is not necessarily the projection on $\ker Y^n$ (a pair of eigenvalues $\pm i\alpha^n \neq 0$ of Y^n could coalesce to zero for $n \rightarrow +\infty$).

If $x_0 = 0$, then $(x, Y) \in \text{Abn}_0(\mathbb{G}_k)$. Thus, let $x_0 \neq 0$. By our assumption on the sequence (x^n, Y^n) , we have $\pi_i^n(x^n) \neq 0$, for all $i \in \{1, \dots, \ell, \perp\}$, and large n . Since $(x^n, Y^n) \in C_k$, and by the characterization of Section 4.1, we must have $m_0 = \dim(\ker Y) \geq 3$. In this case, $(x, Y) \in \text{Abn}_0(\mathbb{G}_k)$, by (35). This proves that $\overline{C}_k \setminus C_k \subseteq \text{Abn}_0(\mathbb{G}_k)$.

We now prove that $\text{Abn}_0(\mathbb{G}_k) \subsetneq \overline{C}_k$. By the characterization of (35), let $(x, Y) \in W \oplus \wedge^2 W$, where $W \subset \mathbb{R}^k$ is a codimension 2 subspace. Up to an orthogonal transformation, we can assume that $W = \{(x_1, \dots, x_{k-2}, 0, 0)^* \in \mathbb{R}^k\} \simeq \mathbb{R}^{k-2}$, that is

$$(39) \quad x = \begin{pmatrix} x_1 \\ \vdots \\ 0 \end{pmatrix}, \quad Y = \begin{pmatrix} Y_1 & \\ & \mathbb{0}_2 \end{pmatrix}, \quad x_1 \in W, \quad Y_1 \in \wedge^2 W.$$

Let (x^n, Y^n) be the sequence with $x^n = x$, and Y^n obtained from Y by replacing the lower right block $\mathbb{0}_2$ with $\frac{1}{n} \mathbb{J}_2$. Then $(x^n, Y^n) \in C_k$ for all n , and the sequence converges to the given abnormal point (x, Y) . This proves $\text{Abn}_0(\mathbb{G}_k) \subseteq \overline{C}_k$. The inclusion is strict, for all $k \geq 2$, since $(x, Y) \in C_k$ does not belong to $\text{Abn}_0(\mathbb{G}_k)$ if Y has maximal rank.

To conclude the proof, for each $k \geq 4$, we give an example of cut point $(x, Y) \in C_k \cap \text{Abn}_0(\mathbb{G}_k)$, reached by an abnormal minimizing geodesic. Let

$$(40) \quad x = 0, \quad Y = \begin{pmatrix} \alpha \mathbb{J}_2 & \\ & \mathbb{0}_{k-2} \end{pmatrix}, \quad \alpha > 0.$$

It is not hard to prove that the geodesics $\gamma : [0, 1] \rightarrow \mathbb{G}_k$ with control $u(t) = e^{-t\Omega}p$, with

$$(41) \quad p = \begin{pmatrix} p_0 \\ 0 \end{pmatrix}, \quad \Omega = \begin{pmatrix} 2\pi \mathbb{J}_2 & \\ & \mathbb{0}_{k-2} \end{pmatrix}, \quad p_0 \in \mathbb{R}^2, \quad |p_0|^2 = 4\pi\alpha,$$

joins the origin with the given point and is abnormal. The formula for the distance in Appendix A yields $d((0, 0), (x, Y))^2 = 4\pi\alpha = L(\gamma)^2$, yielding the minimality property of γ . By Theorem 11, all elements of C_k are cut points, therefore $t_{\text{cut}}(\gamma) = 1$. \square

5. SMALL TIME HEAT KERNEL ASYMPTOTICS

Any sub-Riemannian manifold equipped with a smooth measure supports an intrinsic hypoelliptic operator, the *sub-Laplacian*, playing the role of the Laplace-Beltrami operator of Riemannian geometry. In the case of Carnot groups equipped with a left-invariant measure – and in particular for \mathbb{G}_k – the sub-Laplacian is the “sum of squares” given by

$$(42) \quad \Delta := \sum_{i=1}^k X_i^2.$$

Let $K_t(q', q)$ denote the *heat kernel* of Δ , that is the fundamental solution of the heat equation $\partial_t \psi = \Delta \psi$. Its existence and smoothness for $t > 0$ on complete sub-Riemannian manifolds is classical, see [Str86]. A well known result due to Léandre [Léa87a, Léa87b] yields the relation between the heat kernel and the sub-Riemannian distance:

$$(43) \quad \lim_{t \rightarrow 0^+} 4t \log K_t(q, q') = -d(q, q')^2.$$

Furthermore, the singularity of the heat kernel for $t \rightarrow 0$ depend on the “amount” of minimizing geodesics joining q with q' (see [BBN12] and references therein).

For what concerns Carnot groups of step 2, an integral representation for $K_t(q) := K_t(q, 0)$ has been obtained in [BGG96, Thm. 4] (the general case can be easily recovered by left-invariance). For \mathbb{G}_k , and in our notation, such a formula reads

$$(44) \quad K_t(x, Y) = \frac{2}{(4\pi t)^{k^2/2}} \int_{\wedge^2 \mathbb{R}^k} \sqrt{\frac{\det(B)}{\det \sin(B)}} \cos\left(\frac{\text{Tr}(BY^*)}{2t}\right) e^{-\frac{x^* B \cot(B)x}{4t}} dB,$$

where dB is the Lebesgue measure of $\wedge^2 \mathbb{R}^k \simeq \mathbb{R}^{k(k-1)/2}$, and analytic functions of a matrix are defined by their power series. As an application of our results, combined with the ones in [BBCN16], we mention the following small time asymptotic result.

Theorem 13. *Let $(x, Y) \in C_k \setminus \text{Abn}_0(\mathbb{G}_k)$. Then there exists a constant $C > 0$ such that,*

$$(45) \quad K_t(x, Y) \geq \frac{C + O(t)}{t^{(n+N(x, Y))/2}} e^{-d_0^2(x, Y)/4t}, \quad \text{as } t \rightarrow 0,$$

where d_0 is the sub-Riemannian distance from the origin, $n = \dim(\mathbb{G}_k) = k(k+1)/2$, and $N(x, Y)$ is given by Proposition 6 in terms of the normal form of the point (x, Y) .

Proof. Let (p, Ω) be the initial covector corresponding to a minimizing curve with control $u(t) = e^{-\Omega t}p$, joining the origin with $(x, Y) \in C_k$. By Proposition 6, there exists a continuous family of distinct minimizing geodesics with the same endpoints. The set of initial covectors of this family is

$$(46) \quad \mathcal{O} = \{(Mp, M\Omega M^*) \mid M \in \mathcal{M}(x, Y)\} \subset T_{(x, Y)}^* \mathbb{G}_k \simeq \mathbb{G}_k,$$

where $\mathcal{M}(x, Y)$ is the Lie subgroup of isometries discussed in Section 4.1. In particular, \mathcal{O} is an $N(x, Y)$ -dimensional manifold, and C_k are critical values of the sub-Riemannian exponential map $\exp_0 : T_0^* \mathbb{G}_k \rightarrow \mathbb{G}_k$, which sends (p, Ω) to the point at time 1 of the curve with control $u(t) = e^{-t\Omega} p$. Moreover, $\dim(\ker d_\lambda) \exp_0 \geq N(x, Y)$, for all points $\lambda \in \mathcal{O}$.

Since $(x, Y) \notin \text{Abn}_0(\mathbb{G}_k)$, then all geodesic $\gamma : [0, 1] \rightarrow M$ of this family are normal. Being the sub-Riemannian structure on \mathbb{G}_k real-analytic, then these geodesics are also *strongly normal* (that is, any restriction $\gamma|_{[0, t]}$, for $t \in (0, 1]$, is not abnormal, see [ABR13, Prop. 3.12]). A straightforward modification of [BBN16, Thm. 16] yields the result. \square

6. CLOSING REMARKS AND OPEN PROBLEMS

6.1. Historical remarks. The seminal papers by Gaveau [Gav77] and Brockett [Bro82] mentioned in the introduction contain general statements on the minimization problem on \mathbb{G}_k some of which are left unproven. These results might be useful to determine the true shape of $\text{Cut}_0(\mathbb{G}_k)$, and we list them here, commenting their implications.

- The third (unproven) statement of [Bro82, Thm. 2] asserts that any two optimal controls $u_i(t)$, $i = 1, 2$, such that the associated geodesics γ_i join $(0, 0)$ with (x, Y) are related by $u_1(t) = \theta u_2(t)$ for some orthogonal matrix such that $\theta Y \theta^* = Y$. We were not able neither to prove nor to disprove this claim. However, if true, it would imply that $\overline{C}_k = \overline{\text{Cut}_0(\mathbb{G}_k)}$ (see Proposition 14);
- By Proposition 6, points of C_k are critical values of the sub-Riemannian exponential map (see [ABB15, Rif14]). Consequently, any point $(x, Y) \in C_k$ with $x \perp \ker Y$ is a counter-example to the “only if” part of the fourth claim of [Bro82, Thm. 2];
- For completeness, we recall that, according to [LS95, Appendix A], the result in [Gav77, Thm. 1, p. 133] is false.

Proposition 14. *If the third statement of [Bro82, Thm. 2] is true, then $\overline{C}_k = \overline{\text{Cut}_0(\mathbb{G}_k)}$.*

Proof. For a general sub-Riemannian manifold, let Π_q be the set of points reached by at least two distinct minimizing geodesics, issued from q . By [ABB15, Thm. 8.54], we have,

$$(47) \quad \text{Cut}_q \subseteq \overline{\Pi}_q \cup (\text{Cut}_q \cap \text{Abn}_q).$$

Assume that the third statement of [Bro82, Thm. 2] is true. In particular, if $(x, Y) \in \Pi_0(\mathbb{G}_k)$, there exists a non-trivial $\theta \in \text{O}(k)$ that stabilizes (x, Y) . Then, the discussion about normal forms of points of C_k in Section 4.1 and the characterization (35) imply that $\Pi_0(\mathbb{G}_k) \subseteq C_k \cup \text{Abn}_0(C_k)$. Taking the closure, and using Proposition 12, $\overline{\Pi}_0(\mathbb{G}_k) \subseteq \overline{C}_k$. This, together with (47), imply $\text{Cut}_0(\mathbb{G}_k) \subseteq \overline{C}_k \subseteq \overline{\text{Cut}_0(\mathbb{G}_k)}$, concluding the proof. \square

6.2. The definition of cut locus. The sub-Riemannian cut locus is sometimes defined in the literature as the set of points joined by two distinct minimizing geodesics, see e.g. [AM14, AM16, Agr16]. While this definition might be useful for some statements, it does not correspond to the classical one in the Riemannian case.

6.3. Codimension. Generically, one would expect that the cut locus of a complete sub-Riemannian structure has Hausdorff codimension 1 (with respect to some, and then any, ancillary Riemannian metric). This is indeed the case if there are no abnormal minimizing curves [RT09]. However, Carnot groups are certainly not “generic”, and in fact $\text{codim}(\text{Cut}_0(\mathbb{G}_k)) = 2$ for $k = 2, 3$. By Theorem 11, $\text{codim}(\text{Cut}_0(\mathbb{G}_k)) \leq 2$ for $k \geq 4$. It is reasonable to expect that $\text{codim}(\text{Cut}_0(\mathbb{G}_k)) = 2$ for all k , but this problem remains open.

6.4. Symmetries and geodesic equations. The existing proofs that $\text{Cut}_0(\mathbb{G}_k) = C_k$, for $k = 2, 3$, make heavy use of geodesic equations. We remark that one can prove that $\text{Cut}_0(\mathbb{G}_2) = C_2$ with a purely symmetry argument. Indeed, the invariance of the cut locus by dilations and isometries implies that if $(x, z) \in \text{Cut}_0(\mathbb{G}_2)$ and $x \neq 0$, then $(\varepsilon M x, \varepsilon^2 z) \in \text{Cut}_0(\mathbb{G}_2)$, for all $\varepsilon > 0$ and $M \in \text{O}(2)$. This parabola separates \mathbb{G}_2 into two

disconnected regions. Since no minimizing path can cross the parabola at an intermediate time, this yields a contradiction, and implies that $\text{Cut}_0(\mathbb{G}_2) \subseteq \{(x, 0) \mid x \in \mathbb{R}_*^2\} = C_2$. By Theorem 11 – the proof of which, we stress, never uses the integrated geodesic equations – we have $C_2 \subseteq \text{Cut}_0(\mathbb{G}_2)$, which proves the claim.

Unfortunately, this argument does not carry on for rank $k \geq 3$. In order to prove whether $C_k = \text{Cut}_0(\mathbb{G}_k)$, for all k , we believe that a fine analysis of the integrated geodesic equations (and in particular of the vertical component) is required.

APPENDIX A. DISTANCE FROM THE POINTS ON THE VERTICAL SUBSPACE

We compute the distance from the origin of vertical points in \mathbb{G}_k . A very close formula appears as the second statement of [Bro82, Thm. 2], and differs from ours by a factor 4π .

Proposition 15. *Let $(0, Y) \in \mathbb{G}_k$, with $\text{rank}(Y) = 2r$, and let $0 < \alpha_1 \leq \alpha_2 \leq \dots \leq \alpha_r$ be the (possibly repeated) absolute values of the non-zero eigenvalues of Y . Then,*

$$(48) \quad d((0, 0), (0, Y))^2 = 4\pi \sum_{j=1}^r (r - j + 1) \alpha_j.$$

Proof. Without loss of generality, Let $\gamma(t) = (x(t), Y(t))$ a geodesic from the origin such that $x(1) = 0$ and $Y(1) = Y$, with control $u(t) = e^{-\Omega t} p$. By (14), we have

$$(49) \quad \int_0^1 e^{-t\Omega} p dt = 0.$$

Thus, the non-zero eigenvalues of Ω are of the form $\pm i2\pi\phi$, with $\phi \in \mathbb{N}$. By Remark 3, and up to an orthogonal transformation, we assume that $\Omega = \text{diag}(2\pi\phi_1 \mathbb{J}_2, \dots, 2\pi\phi_\ell \mathbb{J}_2, \mathbb{0}_{k-2\ell})$, with all simple eigenvalues, $2\ell = \text{rank}(\Omega)$, and with distinct $\phi_i \in \mathbb{N}$. We split accordingly $p = (p_1, \dots, p_\ell, p_0)$, with $p_i \in \mathbb{R}^2$ for $i = 1, \dots, \ell$ and $p_0 \in \mathbb{R}^{k-2\ell}$. Under these assumptions, it is not hard to integrate the vertical part of the geodesic equations (14). We obtain

$$(50) \quad Y(1) = \text{diag} \left(\frac{|p_1|^2}{4\pi\phi_1}, \dots, \frac{|p_\ell|^2}{4\pi\phi_\ell}, \mathbb{0}_{k-2\ell} \right).$$

Then, $2\ell = 2r$, and $|p_j|^2 = 4\pi\phi_j\alpha_j$ for all $j = 1, \dots, r$. The squared length of γ is

$$(51) \quad L(\gamma)^2 = \left(\int_0^1 |u(t)| dt \right)^2 = |p|^2 = \sum_{j=1}^r |p_j|^2 = 4\pi \sum_{j=1}^r \phi_j \alpha_j.$$

The minimum of the length is obtained when $\phi_j = r - j + 1$, for all $j = 1, \dots, r$. \square

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