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COMPENSATED COMPACTNESS FOR DIFFERENTIAL FORMS IN CARNOT GROUPS AND APPLICATIONS

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Abstract. In this paper we prove a compensated compactness theorem for differential forms of the intrinsic complex of a Carnot group. The proof relies on a $L^s$–Hodge decomposition for these forms. Because of the lack of homogeneity of the intrinsic exterior differential, Hodge decomposition is proved using the parametrix of a suitable 0-order Laplacian on forms.

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1. Introduction

In the last few years, so-called subriemannian structures have been largely studied in several respects, such as differential geometry, geometric measure theory, subelliptic differential equations, complex variables, optimal control theory, mathematical models in neurosciences, non-holonomic mechanics, robotics. Roughly speaking, a subriemannian structure on a manifold $M$ is defined by a subbundle $H$ of the tangent bundle $TM$, that defines the “admissible” directions at any point of $M$ (typically, think of a mechanical system with non-holonomic constraints). Usually, $H$ is called the horizontal bundle. If we endow each fiber $H_x$ of $H$ with a scalar product $\langle \cdot, \cdot \rangle_x$, there is a naturally associated distance $d$ on $M$, defined as the Riemannian length of the horizontal curves on $M$, i.e. of the curves $\gamma$ such that $\gamma'(t) \in H_{\gamma(t)}$.

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Nowadays, the distance $d$ is called Carnot-Carathéodory distance associated with $H$, or control distance, since it can be viewed as the minimal cost of a control problem, with constraints given by $H$.

Among all subriemannian structures, a prominent position is taken by the so-called Carnot groups (simply connected Lie groups $G$ with stratified nilpotent algebra $\mathfrak{g}$; see e.g. [3], [26], [28]), which play versus subriemannian spaces the role played by Euclidean spaces (considered as tangent spaces) versus Riemannian manifolds. In this case, the first layer of the stratification of the algebra – that can be identified with a linear subspace of the tangent space to the group at the origin – generates by left translation our horizontal subbundle. Through the exponential map, Carnot groups can be identified with the Euclidean space $\mathbb{R}^n$ endowed with a (non-commutative) group law, where $n = \dim \mathfrak{g}$.

In this picture, horizontal vector fields (i.e. sections of $H$) are the natural counterpart of the vector fields in Euclidean spaces. In the Euclidean setting, several questions in pde’s and calculus of variations (like, e.g., non-periodic homogenization for second order elliptic equations or semicontinuity of variational functional in elasticity) can be reduced to the following problem: given two sequences $(E_k)_k$ and $(D_n)_n$ of vector fields weakly convergent in $L^2(\mathbb{R}^n)$, what can we say about the convergence of their scalar product? The compensated compactness (or div–curl) theorem of Murat and Tartar ([18], [19]) provides an answer: it states basically that the scalar product $(E_k, D_k)$ still converges in the sense of distributions, provided $\{\text{div } D_k : k \in \mathbb{N}\}$ and $\{\text{curl } E_k : k \in \mathbb{N}\}$ are compact in $H^{-1}_\text{loc}(\mathbb{R}^n)$ and $(H^{-1}_\text{loc}(\mathbb{R}^n))^{n(n-1)/2}$, respectively.

When attacking for instance the study of the non-periodic homogenization of differential operators in a Carnot group $G$, it is natural to look for a similar statement for horizontal vector fields in $G$. In fact, a preliminary difficulty consists in finding the appropriate notion of divergence and curl operators for horizontal vector fields in Carnot groups. To this end, it is convenient to write our problem in terms of differential forms, and to attack the more general problem of compensated compactness for sequences of differential forms. Indeed, we can identify each vector field $E_k$ with a 1-form $\eta_k$, and each vector field $D_k$ with the 1-form $\gamma_k$. Then, the compactness of curl $E_k$ is equivalent to the compactness of $d\eta_k$. Analogously, denoting by $*$ the Hodge duality operator, the compactness of div $D_k$ is equivalent to the compactness of $*d(\ast \gamma_k)$, and hence to the compactness of $d(\ast \gamma_k)$. With these notations, if $\varphi$ is a smooth function with compact support and $dV$ denotes the volume element in $\mathbb{R}^n$, then $(E_k, D_k)\varphi dV = \varphi \eta_k \wedge \ast \gamma_k$.

Thus, a natural formulation of the compensated compactness theorem in the De Rham complex $(\Omega, d)$ reads as follows (see, e.g., [14] and [21]):

If $1 < s_i < \infty$, $0 \leq h_i \leq n$ for $i = 1, 2$, and $0 < \varepsilon < 1$, assume that $\alpha_\varepsilon^{s_i} \in L^{s_i}_\text{loc}(\mathbb{R}^n, \Omega^{h_i})$ for $i = 1, 2$, where $\frac{1}{s_1} + \frac{1}{s_2} = 1$ and $h_1 + h_2 = n$. Assume that

\begin{equation}
\alpha_\varepsilon^{s_i} \rightharpoonup \alpha_i \text{ weakly in } L^{s_i}_\text{loc}(\mathbb{R}^n, \Omega^{h_i}) \quad \text{as } \varepsilon \to 0,
\end{equation}

and that

\begin{equation}
\{d\alpha_\varepsilon^{s_i}\} \text{ is pre-compact in } W^{-1,s_i}_\text{loc}(\mathbb{R}^n, \Omega^{h_i+1})
\end{equation}
for \( i = 1, 2 \).

Then
\[
(3) \quad \int_{\mathbb{R}^n} \varphi \alpha_1^\varepsilon \wedge \alpha_2^\varepsilon \to \int_{\mathbb{R}^n} \varphi \alpha_1 \wedge \alpha_2 \quad \text{as} \ \varepsilon \to 0
\]

for any \( \varphi \in \mathcal{D}(\mathbb{R}^n) \).

Thus, when dealing with Carnot groups, we are reduced preliminarily to look for a somehow “intrinsic” notion of differential forms such that

- Intrinsic 1–forms should be horizontal 1–forms, i.e. forms that are dual of horizontal vector fields, where by duality we mean that, if \( v \) is a vector field in \( \mathbb{R}^n \), then its dual form \( v^\flat \) acts as \( v^\flat(w) = \langle v, w \rangle \), for all \( w \in \mathbb{R}^n \).

- A somehow “intrinsic” notion of exterior differential acting between intrinsic forms. Again, the intrinsic differential of a smooth function, should be its horizontal differential (that is dual operator of the gradient along a basis of the horizontal bundle).

- “Intrinsic forms” and the “intrinsic differential” should define a complex that is exact and self-dual under Hodge \( * \)-duality.

It turns out that such a complex (in fact a sub-complex of the De Rham complex) has been defined and studied by M. Rumin in [25] and [24] ([23] for contact structures), so that we are provided with a good setting for our theory. For sake of self-consistency of the paper, we present in Section 2 the main features of this complex, that will be denoted by \( (E_0^s, d_c) \), where \( d_c : E_0^h \to E_0^{h+1} \) is a suitable exterior differential. We stress now that a crucial property of \( d_c \) relies on the fact that it is in general a non homogeneous higher order differential operator. To better understand how this feature affects the compensated compactness theorem, we begin by sketching the basic steps of the proof in the Euclidean setting. The crucial point consists in proving the following Hodge type decomposition: if \( 0 < \varepsilon < 1 \), let \( \alpha^\varepsilon \) be compactly supported differential \( h \)-forms such that

\[
(4) \quad \alpha^\varepsilon \to \alpha \quad \text{as} \ \varepsilon \to 0 \quad \text{weakly in} \quad L^s(\mathbb{R}^n)
\]

and

\[
(5) \quad \{d\alpha^\varepsilon\} \quad \text{is compact in} \quad W^{-1,s}_{\text{loc}}(\mathbb{R}^n).
\]

Then there exist \( h \)-forms \( \omega^\varepsilon \) and \((h - 1)\)-forms \( \psi^\varepsilon \) such that

- \( \omega^\varepsilon \to \omega \) strongly in \( L^s_{\text{loc}}(\mathbb{R}^n) \);
- \( \psi^\varepsilon \to \psi \) strongly in \( L^s_{\text{loc}}(\mathbb{R}^n) \);
- \( \alpha^\varepsilon = \omega^\varepsilon + d\psi^\varepsilon \).

Roughly speaking (for instance, modulo suitable cut-off functions), the proof of the decomposition can be carried out as follows (see e.g. [21]).

- let \( \Delta := \delta d + d\delta \) be the Laplace operator on \( k \)-forms, where \( \delta = d^* \) is the \( L^2 \) formal adjoint of \( d \);
- we write
  \[
  \alpha^\varepsilon = \Delta^{-1} \delta \alpha^\varepsilon = \delta d \Delta^{-1} \alpha^\varepsilon + d\delta \Delta^{-1} \alpha^\varepsilon
  \]
- we set
  \[
  \omega^\varepsilon := \delta d \Delta^{-1} \alpha^\varepsilon = \delta \Delta^{-1} d\alpha^\varepsilon
  \]
that is strongly compact in $L^s_{\text{loc}}(\mathbb{R}^n)$, since $d\alpha^\varepsilon$ is strongly compact in $W^{1,s}_{\text{loc}}(\mathbb{R}^n)$;

- we set

$$\psi^\varepsilon := \delta \Delta^{-1} \alpha^\varepsilon$$

that converges weakly in $W^{1,s}_{\text{loc}}(\mathbb{R}^n)$ and hence strongly in $L^s_{\text{loc}}(\mathbb{R}^n)$.

If we want to repeat a similar argument, we face several difficulties. First of all, the “naïf Laplacian” associated with $d_e$, i.e.

$$\delta_e d_e + d_e \delta_e$$

where $\delta_e = d_e^*$, in general is not homogeneous. Even if $d_e$ is homogeneous, as in the Heisenberg group $\mathbb{H}^n$, such a “Laplacian” is not homogeneous. For instance, on 1–forms in $\mathbb{H}^1$, $\delta_e d_e$ is a 4th order operator, while $d_e \delta_e$ is a 2nd order one. This is due to the fact that the order of $d_e$ depends on the order of the forms on which it acts on. In fact, $d_e$ on 1–forms in $\mathbb{H}^1$ is a 2nd order operator, as well as its adjoint $\delta_e$ (which acts on 2–form), while $\delta_e$ on 1–forms is a first order operator, since it is the adjoint of $d_e$ on 0–forms, which is a first order operator.

Though in the particular case of 1–forms in $\mathbb{H}^1$ this difficulty can be overcame as in [2], by using the suitable homogeneous 4th order operator $\delta_e d_e + (d_e \delta_e)^2$ defined by Rumin ([23]) that satisfies also sharp a priori estimates, the general situation requires different arguments.

In general, the lack of homogeneity of $d_e$ can be described through the notion of weight of vector fields and, by duality, of differential forms (see [25]). Elements of the $j$-th layer of $\mathfrak{g}$ are said to have (pure) weight $w = j$; by duality, a 1-form that is dual of a vector field of (pure) weight $w = j$ will be said to have (pure) weight $w = j$. Vector fields in the direct sum of the first $j - 1$ layers of $\mathfrak{g}$ are said to have weight $w < j$. Thus, a 1-form is said to have weight $w \geq j$ if it vanishes on all vectors of weight $w < j$. This procedure can be extended to $h$–forms. Clearly, there are forms that have no pure weight, but we can decompose $E^h_0$ in the direct sum of orthogonal spaces of forms of pure weight, and therefore we can find a basis of $E^h_0$ given by orthonormal forms of increasing pure weights. We refer to such a basis as to a basis adapted to the filtration of $E^h_0$ induced by the weight.

Then, once suitable adapted bases of $h$–forms and $(h+1)$–forms are chosen, $d_e$ can be viewed as a matrix–valued operator such that, if $\alpha$ has weight $p$, then the component of weight $q$ of $d_e \alpha$ is given by a differential operator in the horizontal derivatives of order $q - p \geq 1$, acting on the components of $\alpha$.

The following two simple examples can enlight the phenomenon. We restrict ourselves to 1–forms, and therefore we need to describe only $E^0_0$ and $E^2_0$. For more examples and proofs of the statements, see Appendix B.

Let $\mathbb{G} := \mathbb{H}^1 \equiv \mathbb{R}^3$ be the first Heisenberg group, with variables $(x, y, t)$. Set $X := \partial_x + 2yt \partial_t$, $Y := \partial_y - 2xt \partial_t$, $T := \partial_t$. The dual forms are respectively $dx$, $dy$ and $\theta$, where $\theta$ is the contact form of $\mathbb{H}^1$. The stratification of the algebra $\mathfrak{g}$ is given by $\mathfrak{g} = V_1 \oplus V_2$, where $V_1 = \text{span} \{X,Y\}$ and $V_2 = \text{span} \{T\}$. In this case, $E^0_0 = \text{span} \{dx,dy\}$ and $E^2_0 = \text{span} \{dx \wedge \theta,dy \wedge \theta\}$. These forms have respectively weight 1 (1–forms) and 3 (2–forms).
1-forms, the exterior differential $d_c$ acts as follows:

$$d_c(\alpha X dx + \alpha_Y dy) = -\frac{1}{4}(X^2 \alpha_Y - 2XY\alpha_X + YX\alpha_X)dx \wedge \theta$$

$$- \frac{1}{4}(2YX\alpha_Y - Y^2\alpha_X - XY\alpha_Y)dy \wedge \theta$$

$$:= P_1(\alpha_X,\alpha_Y)dx \wedge \theta + P_2(\alpha_X,\alpha_Y)dy \wedge \theta.$$

Notice that $P_1, P_2$ are homogeneous operators of order 2 (=3-1) in the horizontal derivatives.

Consider now a slightly different setting. Let $G := \mathbb{H} \times \mathbb{R}$, and denote by $(x,y,t)$ the variables in $\mathbb{H}$ and by $s$ the variable in $\mathbb{R}$. Set $X, Y, T$ as above, and $S := \partial_s$. The dual form of $S$ is $ds$. The stratification of the algebra $g$ is given by $g = V_1 \oplus V_2$, where $V_1 = \text{span} \{X, Y, S\}$ and $V_2 = \text{span} \{T\}$. In this case $E^1_0 = \text{span} \{dx, dy, ds\}$ and $E^2_0 = \text{span} \{dx \wedge ds, dy \wedge ds, dx \wedge \theta, dy \wedge \theta\}$. Thus, all 1-forms have weight 1, whereas 2-forms have weight 2 ($dx \wedge ds$ and $dy \wedge ds$) and 3 ($dx \wedge \theta$ and $dy \wedge \theta$). The exterior differential $d_c$ on 1-forms acts as follows:

$$d_c(\alpha X dx + \alpha_Y dy + \alpha_S ds) = P_1(\alpha_X,\alpha_Y)dx \wedge \theta$$

$$+ P_2(\alpha_X,\alpha_Y)dy \wedge \theta + (X\alpha_S - S\alpha_X)dx \wedge ds + (Y\alpha_S - S\alpha_Y)dy \wedge ds,$$

where $P_1, P_2$ have been defined above. Thus, the components of $d_c$ are homogeneous differential operators of order 2 or 1.

To overcome the difficulties arising from the lack of homogeneity of $d_c$, we rely on an argument introduced in [25] (when dealing with the notion of CC-elliptic complex). Let us give a non rigorous sketch of the argument. Denote by $\Delta_G$ the positive scalar sublaplacian associated with a basis of the first layer of $g$ ($\Delta_G$ is a Hörmander’s sum-of-squares operator). Remember that, once adapted bases of $E^0_0$ and $E^{n+1}_0$ are chosen, $d_c$ can be viewed as a matrix-valued differential operator, whose entries are homogeneous operators in the horizontal derivatives. Then we can multiply $d_c$ from the left and from the right by suitable diagonal matrices whose entries are positive or negative fractional powers of $\Delta_G$, in such a way that all entries of the resulting matrix-valued operator are 0-order operators. By the way, this notion of order of an operator, as well as all combination rules that are applied, have a precise meaning only in the setting of a pseudodifferential calculus. We rely on the CGGP-calculus (see [5] and Appendix A). In such a way, we obtain a “0-order exterior differential” $\tilde{d}_c$, and eventually a “0-order Laplacian” $\tilde{d}_c(\tilde{d}_c)^* + (\tilde{d}_c)^*\tilde{d}_c$, that, thanks to [25] and [5], has both a right and a left parametrix. Thus, we can mimic the proof we have sketched above for the De Rham complex (again, to work in a precise pseudodifferential calculus allows the composition of different operators).

It is worth noticing that the lack of homogeneity of the exterior differential $d_c$ affects also the natural hypotheses we assume in order to prove Hodge decomposition and compensated compactness theorem for forms in $E_0$. Indeed, in the Euclidean setting, assumptions (4) and (5) are naturally correlated by the fact that the exterior differential $d$ is a homogeneous operator of order 1, which maps continuously $L^s_{\text{loc}}(\mathbb{R}^n)$ into $W^{-1,s}_{\text{loc}}(\mathbb{R}^n)$. Instead, when we are dealing with the complex $(E_0^0, d_c)$, given a sequence of
$h$-forms $\alpha^\varepsilon$ that converges weakly $L^h_{oc}(\mathbb{R}^n, E_0^h)$, then the different components of $d_c \alpha^\varepsilon$ converge weakly in Sobolev spaces of different negative orders, according to the weight of the different components. For instance, if we denote by $W^{-k,s}_{G,loc}(\mathbb{R}^n)$ the Sobolev space of negative order $-k$ associated with horizontal derivatives (see Section 3), then in our model examples $\mathbb{H}^1$ and $\mathbb{H}^1 \times \mathbb{R}$, with an obvious meaning of the notations, assumption (5) for 1-forms becomes

$$\{ P_i(\alpha^\varepsilon_X, \alpha^\varepsilon_Y) \} \text{ compact in } W^{-2,s}_{G,loc}(\mathbb{R}^n), \quad i = 1, 2,$$

when $G = \mathbb{H}^1$, and

$$\{ P_i(\alpha^\varepsilon_X, \alpha^\varepsilon_Y) \} \text{ compact in } W^{-2,s}_{G,loc}(\mathbb{R}^n), \quad i = 1, 2,$$

as well as

$$\{ X\alpha^\varepsilon_S - S\alpha^\varepsilon_X \}, \{ Y\alpha^\varepsilon_S - S\alpha^\varepsilon_Y \} \text{ compact in } W^{-1,s}_{G,loc}(\mathbb{R}^n)$$

when $G = \mathbb{H}^1 \times \mathbb{R}$.

Our compensated compactness result for horizontal vector fields is contained in its simplest form in Theorem 5.1, that can be derived by standard arguments from a general statement (Theorem 4.13) for intrinsic differential $h$-forms, that holds whenever all intrinsic $h$-forms have the same pure weight (this is always true if $h=1$).

In Section 2 we establish most of the notations, and we collect more or less known results about Carnot groups and the basic ingredients of Rumin’s theory. In Section 3 we introduce from the functional point of view all the function spaces we need in the sequel, with a special attention for negative order spaces (which turn out to be spaces of currents). Moreover we emphasize the connections between our function spaces and the pseudodifferential operators of the CGGP-calculus. In Section 4 we establish and we prove our main results: Hodge decomposition and compensated compactness for forms (Theorems 4.1 and 4.13). In Section 5 we apply our main results to prove a div–curl theorem for horizontal vector fields (Theorem 5.1). We illustrate several different explicit examples, and we apply the theory to the study of the H-convergence of divergence form second order differential operators in Carnot groups. In Appendix A we summarize the basic facts of the theory of pseudodifferential operators in homogeneous groups as given in [5]. Moreover, we prove representation theorems and continuity properties for pseudodifferential operators in our scale of Sobolev spaces. Finally, in Appendix B we write explicitly the structure of the intrinsic differential $d_c$ and we analyze a list of detailed examples.

2. Preliminary results and notations

A Carnot group $G$ of step $\kappa$ is a simply connected Lie group whose Lie algebra $\mathfrak{g}$ has dimension $n$, and admits a step $\kappa$ stratification, i.e. there exist linear subspaces $V_1, \ldots, V_\kappa$ such that

$$\mathfrak{g} = V_1 \oplus \ldots \oplus V_\kappa, \quad [V_i, V_j] = V_{i+j}, \quad V_\kappa \neq \{0\}, \quad V_i = \{0\} \text{ if } i > \kappa,$$

where $[V_i, V_j]$ is the subspace of $\mathfrak{g}$ generated by the commutators $[X, Y]$ with $X \in V_i$ and $Y \in V_j$. Let $m_i = \dim(V_i)$, for $i = 1, \ldots, \kappa$ and $h_i = m_1 + \cdots + m_i$.
with \( h_0 = 0 \) and, clearly, \( h_\kappa = n \). Choose a basis \( e_1, \ldots, e_n \) of \( \mathfrak{g} \) adapted to the stratification, i.e. such that
\[
e_{h_{j-1}+1}, \ldots, e_{h_j} \text{ is a basis of } V_j \text{ for each } j = 1, \ldots, \kappa.
\]
Let \( X = \{X_1, \ldots, X_n\} \) be the family of left invariant vector fields such that \( X_i(0) = e_i \). Given (6), the subset \( X_1, \ldots, X_{m_1} \) generates by commutations all the other vector fields; we will refer to \( X_1, \ldots, X_{m_1} \) as generating vector fields of the group. The exponential map is a one to one map from \( \mathfrak{g} \) onto \( \mathbb{G} \), i.e. any \( p \in \mathbb{G} \) can be written in a unique way as \( p = \exp(p_1X_1 + \cdots + p_nX_n) \). Using these exponential coordinates, we identify \( p \) with the \( n \)-tuple \( (p_1, \ldots, p_n) \in \mathbb{R}^n \) and we identify \( \mathbb{G} \) with \( (\mathbb{R}^n, \cdot) \), where the explicit expression of the group operation \( \cdot \) is determined by the Campbell-Hausdorff formula. If \( p \in \mathbb{G} \) and \( i = 1, \ldots, \kappa \), we put \( p^i = (p_{h_i-1+1}, \ldots, p_{h_i}) \in \mathbb{R}^{m_i} \), so that we can also identify \( p \) with \( (p^1, \ldots, p^n) \in \mathbb{R}^{m_1} \times \cdots \times \mathbb{R}^{m_n} = \mathbb{R}^n \).

Two important families of automorphism of \( \mathbb{G} \) are the group translations and the group dilations of \( \mathbb{G} \). For any \( x \in \mathbb{G} \), the (left) translation \( \tau_x : \mathbb{G} \to \mathbb{G} \) is defined as
\[
z \mapsto \tau_x z := x \cdot z.
\]
For any \( \lambda > 0 \), the dilation \( \delta_\lambda : \mathbb{G} \to \mathbb{G} \), is defined as
\[
\delta_\lambda(x_1, \ldots, x_n) = (\lambda^{d_1} x_1, \ldots, \lambda^{d_n} x_n),
\]
where \( d_i \in \mathbb{N} \) is called homogeneity of the variable \( x_i \) in \( \mathbb{G} \) (see [10] Chapter 1) and is defined as
\[
d_j = i \quad \text{whenever } h_{i-1} + 1 \leq j \leq h_i,
\]
hence \( 1 = d_1 = \cdots = d_{m_1} < d_{m_1+1} = 2 \leq \cdots \leq d_n = \kappa \).

The Lie algebra \( \mathfrak{g} \) can be endowed with a scalar product \( \langle \cdot, \cdot \rangle \), making \( \{X_1, \ldots, X_n\} \) an orthonormal basis.

As customary, we fix a smooth homogeneous norm \( |\cdot| \) in \( \mathbb{G} \) such that the gauge distance \( d(x, y) := |y^{-1}x| \) is a left-invariant true distance, equivalent to the Carnot-Carathéodory distance in \( \mathbb{G} \) (see [26], p.638). We set \( B(p, r) = \{q \in \mathbb{G}: d(p, q) < r \} \).

The Haar measure of \( \mathbb{G} = (\mathbb{R}^n, \cdot) \) is the Lebesgue measure \( \mathcal{L}^n \) in \( \mathbb{R}^n \). If \( A \subset \mathbb{G} \) is \( \mathcal{L} \)-measurable, we write also \( |A| := \mathcal{L}(A) \).

We denote by \( Q \) the homogeneous dimension of \( \mathbb{G} \), i.e. we set
\[
Q := \sum_{i=1}^\kappa i \dim(V_i).
\]
Since for any \( x \in \mathbb{G} \) \( |B(x, r)| = |B(e, r)| = r^Q|B(e, 1)| \), \( Q \) is the Hausdorff dimension of the metric space \( (\mathbb{G}, d) \).

**Proposition 2.1.** The group product has the form
\[
x \cdot y = x + y + Q(x, y), \quad \text{for all } x, y \in \mathbb{R}^n
\]
where \( Q = (Q_1, \ldots, Q_n) : \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^n \) and each \( Q_i \) is a homogeneous polynomial of degree \( d_i \) with respect to the intrinsic dilations of \( \mathbb{G} \) defined in (7), that is
\[
Q_i(\delta_\lambda x, \delta_\lambda y) = \lambda^{d_i} Q_i(x, y), \quad \text{for all } x, y \in \mathbb{G}.
\]
Moreover, again for all \( x, y \in G \)
\[
Q_1(x, y) = \ldots = Q_{m_1}(x, y) = 0,
\]
(10)
\[
Q_j(x, 0) = Q_j(0, y) = 0 \quad \text{and} \quad Q_j(x, x) = Q_j(x, -x) = 0, \quad \text{for} \ m_1 < j \leq n,
\]
(11)
\[
Q_j(x, y) = Q_j(x_1, \ldots, x_{h_i-1}, y_1, \ldots, y_{h_i-1}), \quad \text{if} \ 1 < i \leq \kappa \quad \text{and} \ j \leq h_i.
\]

Note that from Proposition 2.1 it follows that
\[
\delta_x x \cdot \delta_y y = \delta_x (x \cdot y)
\]
and that the inverse \( x^{-1} \) of an element \( x = (x_1, \ldots, x_n) \in (\mathbb{R}^n, \cdot) \) has the form
\[
x^{-1} = (-x_1, \ldots, -x_n).
\]

**Proposition 2.2** (see, e.g.[11], Proposition 2.2). The vector fields \( X_j \) have polynomial coefficients and have the form

\[
X_j(x) = \partial_j + \sum_{i > h_i}^{n} q_{i,j}(x) \partial_i, \quad \text{for} \ j = 1, \ldots, n \quad \text{and} \ j \leq h_i,
\]
(12)

where \( q_{i,j}(x) = \frac{\partial Q_j}{\partial y_j}(x, y)|_{y = 0} \) so that if \( j \leq h_i \) then \( q_{i,j}(x) = q_{i,j}(x_1, \ldots, x_{h_i-1}) \) and \( q_{i,j}(0) = 0 \).

The subbundle of the tangent bundle \( TG \) that is spanned by the vector fields \( X_1, \ldots, X_{m_1} \) plays a particularly important role in the theory, and it is called the **horizontal bundle** \( HG \); the fibers of \( HG \) are
\[
HG_x = \text{span} \{X_1(x), \ldots, X_{m_1}(x)\}, \quad x \in G.
\]

From now on, for sake of simplicity, sometimes we set \( m := m_1 \).

A subriemannian structure is defined on \( G \), endowing each fiber of \( HG \) with a scalar product \( \langle \cdot, \cdot \rangle_x \) and with a norm \( | \cdot |_x \) making the basis \( X_1(x), \ldots, X_m(x) \) an orthonormal basis.

The sections of \( HG \) are called **horizontal sections**, and a vector of \( HG_x \) is an **horizontal vector**.

If \( f \) is a real function defined in \( G \), we denote by \( \gamma f \) the function defined by \( \gamma f(p) := f(p^{-1}) \), and, if \( T \in D'(G) \), then \( \gamma T \) is the distribution defined by \( \langle \gamma T | \varphi \rangle := \langle T | \gamma \varphi \rangle \) for any test function \( \varphi \).

Following [10], we also adopt the following multi-index notation for higher-order derivatives. If \( I = (i_1, \ldots, i_n) \) is a multi–index, we set \( X^I = X_1^{i_1} \cdots X_n^{i_n} \). By the Poincaré–Birkhoff–Witt theorem (see, e.g. [4], I.2.7), the differential operators \( X^I \) form a basis for the algebra of left invariant differential operators in \( G \). Furthermore, we set \( |I| := i_1 + \cdots + i_n \) the order of the differential operator \( X^I \), and \( d(I) := d_1 i_1 + \cdots + d_n i_n \) its degree of homogeneity with respect to group dilations. From the Poincaré–Birkhoff–Witt theorem, it follows, in particular, that any homogeneous linear differential operator in the horizontal derivatives can be expressed as a linear combination of the operators \( X^I \) of the special form above.
Again following e.g. [10], we can define a group convolution in $G$: if, for instance, $f \in \mathcal{D}(G)$ and $g \in L^1_{loc}(G)$, we set
\[
(13) \quad f \ast g(p) := \int f(q)g(q^{-1}p) \, dq \text{ for } p \in G.
\]
We remind that, if (say) $\psi$ is a smooth function and $L$ is a left invariant differential operator, then $L(f \ast g) = f \ast Lg$. We remind also that the convolution is again well defined when $f, g \in \mathcal{D}'(G)$, provided at least one of them has compact support (as customary, we denote by $\mathcal{E}'(G)$ the class of compactly supported distributions in $G$ identified with $\mathbb{R}^n$). In this case the following identities hold
\[
(14) \quad \langle f \ast g | \varphi \rangle = \langle g^\vee f \ast \varphi \rangle \quad \text{and} \quad \langle f \ast g | \varphi \rangle = \langle f | \varphi \ast g^\vee \rangle
\]
for any test function $\varphi$. Suppose now $f \in \mathcal{E}'(G)$ and $g \in \mathcal{D}'(G)$. Then, if $\psi \in \mathcal{D}(G)$, we have
\[
(15) \quad \langle (W^f f) \ast g | \psi \rangle = \langle W^f f | \psi \ast g^\vee \rangle = (-1)^{|f|}\langle f | \varphi \ast (W^f g^\vee) \rangle
\]
\[
= (-1)^{|f|}\langle f \ast W^f g^\vee | \psi \rangle.
\]

The dual space of $\mathfrak{g}$ is denoted by $\bigwedge^1 \mathfrak{g}$. The basis of $\bigwedge^1 \mathfrak{g}$, dual of the basis $X_1, \ldots, X_n$, is the family of covectors $\{\theta_1, \ldots, \theta_n\}$. We indicate as $\langle \cdot, \cdot \rangle$ also the inner product in $\bigwedge^1 \mathfrak{g}$ that makes $\theta_1, \ldots, \theta_n$ an orthonormal basis.

Following Federer (see [8] 1.3), the exterior algebras of $\mathfrak{g}$ and of $\bigwedge^1 \mathfrak{g}$ are the graded algebras indicated as $\bigwedge^\ast \mathfrak{g} = \bigoplus_{k=0}^n \bigwedge^k \mathfrak{g}$ and $\bigwedge^\ast \bigwedge^1 \mathfrak{g} = \bigoplus_{k=0}^n \bigwedge^k \bigwedge^1 \mathfrak{g}$, where $\bigwedge^0 \mathfrak{g} = \mathbb{R}$ and, for $1 \leq k \leq n$,
\[
\bigwedge^k \mathfrak{g} := \text{span}\{X_{i_1} \wedge \cdots \wedge X_{i_k} : 1 \leq i_1 < \cdots < i_k \leq n\},
\]
\[
\bigwedge^k \bigwedge^1 \mathfrak{g} := \text{span}\{\theta_{i_1} \wedge \cdots \wedge \theta_{i_k} : 1 \leq i_1 < \cdots < i_k \leq n\}.
\]

The elements of $\bigwedge^k \mathfrak{g}$ and $\bigwedge^k \bigwedge^1 \mathfrak{g}$ are called $k$-vectors and $k$-covectors.

We denote by $\Theta^k$ the basis $\{\theta_{i_1} \wedge \cdots \wedge \theta_{i_k} : 1 \leq i_1 < \cdots < i_k \leq n\}$ of $\bigwedge^k \mathfrak{g}$. We remind that
\[
\dim \bigwedge^k \mathfrak{g} = \dim \bigwedge^k \bigwedge^1 \mathfrak{g} = \binom{n}{k}.
\]

The dual space $\bigwedge^1(\bigwedge^k \mathfrak{g})$ of $\bigwedge^k \mathfrak{g}$ can be naturally identified with $\bigwedge^k \mathfrak{g}$. The action of a $k$-covector $\varphi$ on a $k$-vector $v$ is denoted as $\langle \varphi | v \rangle$.

The inner product $\langle \cdot, \cdot \rangle$ extends canonically to $\bigwedge^k \mathfrak{g}$ and to $\bigwedge^k \bigwedge^1 \mathfrak{g}$ making the bases $X_{i_1} \wedge \cdots \wedge X_{i_k}$ and $\theta_{i_1} \wedge \cdots \wedge \theta_{i_k}$ orthonormal.

**Definition 2.3.** We define linear isomorphisms (Hodge duality: see [8] 1.7.8)
\[
*: \bigwedge^k \mathfrak{g} \longleftrightarrow \bigwedge^{n-k} \mathfrak{g} \quad \text{and} \quad *: \bigwedge^k \bigwedge^1 \mathfrak{g} \longleftrightarrow \bigwedge^{n-k} \bigwedge^1 \mathfrak{g}.
\]
for \(1 \leq k \leq n\), putting, for \(v = \sum_I v_I X_I \) and \(\varphi = \sum_I \varphi_I \theta_I\),
\[
* v := \sum_I v_I (* X_I) \quad \text{and} \quad * \varphi := \sum_I \varphi_I (* \theta_I)
\]
where
\[
* X_I := (-1)^{\sigma(I)} X_{I^*} \quad \text{and} \quad * \theta_I := (-1)^{\sigma(I)} \theta_{I^*},
\]
with \(I = \{i_1, \ldots, i_k\}, 1 \leq i_1 < \cdots < i_k \leq n\), \(X_I = X_{i_1} \wedge \cdots \wedge X_{i_k}\), 
\(\theta_I = \theta_{i_1} \wedge \cdots \wedge \theta_{i_k}\), \(I^* = \{i_1^* < \cdots < i_{n-k}^*\} = \{1, \ldots, n\} \setminus I\) and \(\sigma(I)\) is the number of couples \((i_h, i_h^*)\) with \(i_h > i_h^*\).

The following properties of the \(\ast\) operator follow readily from the definition: \(\forall v, w \in \bigwedge^k g\) and \(\forall \varphi, \psi \in \bigwedge^k g\)
\[
(*)v = (-1)^{k(n-k)} v, \quad * * \varphi = (-1)^{k(n-k)} \varphi = \varphi,
\]
\[
\langle * \varphi \rangle * v = \langle \varphi \rangle v.
\]

\(\text{Definition 2.4.}\) For any \(q, q' \in \mathbb{G}\) and for any linear map \(L : T G_q \to T G_{q'}\),
\[
\Lambda_k L : \bigwedge^k T G_q \to \bigwedge^k T G_{q'},
\]
is the linear map defined by
\[
(\Lambda_k L)(v_1 \wedge \cdots \wedge v_k) = L(v_1) \wedge \cdots \wedge L(v_k).
\]

Analogously, we can define
\[
h \bigwedge^k_p := (\Lambda^k T G_q) \bigwedge^k_p
\]
for any \(p \in \mathbb{G}\), where for any linear map \(f : T G_q \to T G_{q'}\)
\[
\Lambda^k f : \bigwedge^k T G_{q'} \to \bigwedge^k T G_q
\]
is the linear map defined by
\[
\langle (\Lambda^k f)(\alpha) \rangle v_1 \wedge \cdots \wedge v_k = \langle \alpha \rangle(\Lambda^k f)(v_1 \wedge \cdots \wedge v_k)
\]
for any \(\alpha \in \bigwedge^k T G_{q'}\) and any simple \(k\)-vector \(v_1 \wedge \cdots \wedge v_k \in h \bigwedge^k T G_q\).

\(\text{Definition 2.5.}\) If \(\alpha \in \bigwedge^1 g\), \(\alpha \neq 0\), we say that \(\alpha\) has \emph{pure weight} \(k\), and we write \(w(\alpha) = k\), if \(\alpha^2 \in V_k\). Obviously,
\[
w(\alpha) = k \quad \text{if and only if} \quad \alpha = \sum_{j = h_{k-1} + 1}^{h_k} \alpha_j \theta_j,
\]
with \(\alpha_{h_{k-1} + 1}, \ldots, \alpha_{h_k} \in \mathbb{R}\). More generally, if \(\alpha \in \bigwedge^h g\), we say that \(\alpha\) has pure weight \(k\) if \(\alpha\) is a linear combination of covectors \(\theta_{i_1} \wedge \cdots \wedge \theta_{i_k}\) with \(w(\theta_{i_1}) + \cdots + w(\theta_{i_k}) = k\).

\(\text{Remark 2.6.}\) If \(\alpha, \beta \in \bigwedge^h g\) and \(w(\alpha) \neq w(\beta)\), then \(\langle \alpha, \beta \rangle = 0\). Indeed, it is enough to notice that, if \(w(\theta_{i_1} \wedge \cdots \wedge \theta_{i_h}) \neq w(\theta_{j_1} \wedge \cdots \wedge \theta_{j_h})\), with \(i_1 < i_2 < \cdots < i_h\) and \(j_1 < j_2 < \cdots < j_h\), then for at least one of the indices \(\ell = 1, \ldots, h\), \(i_\ell \neq j_\ell\), and hence \(\langle \theta_{i_1} \wedge \cdots \wedge \theta_{i_h}, \theta_{j_1} \wedge \cdots \wedge \theta_{j_h} \rangle = 0\).
We have

\[ \bigwedge^h \mathfrak{g} = \bigoplus_{p=\min h}^{\max h} \bigwedge^{h,p} \mathfrak{g}, \]

where \( \bigwedge^{h,p} \mathfrak{g} \) is the linear span of the \( h \)-covectors of weight \( p \).

Since the elements of the basis \( \Theta^h \) have pure weights, a basis of \( \bigwedge^{h,p} \mathfrak{g} \) is given by \( \Theta^{h,p} := \Theta^h \cap \bigwedge^{h,p} \mathfrak{g} \) (in the Introduction, we called such a basis an adapted basis).

As pointed out in Remark 2.6, the decomposition in (17) is orthogonal.

We denote by \( \Pi^{h,p} \) the orthogonal projection of \( \bigwedge^h \mathfrak{g} \) on \( \bigwedge^{h,p} \mathfrak{g} \).

Starting from \( \bigwedge^h \mathfrak{g} \) and \( \bigwedge^e \mathfrak{g} \), we can define by left translation fiber bundles over \( \mathbb{G} \) that we can still denote by \( \bigwedge^h \mathfrak{g} \) and \( \bigwedge^e \mathfrak{g} \), respectively. To do this, for instance we identify \( \bigwedge^h \mathfrak{g} \) with the fiber \( \bigwedge^e \mathfrak{g} \) over the origin, and we define the fiber over \( x \in \mathbb{G} \) as \( \bigwedge^h \mathfrak{g}_x := \Lambda^k(d\tau_{x^{-1}}) \bigwedge^h \mathfrak{g} \). Sections of \( \bigwedge^h \mathfrak{g} \) are called \( h \)-vector fields, and sections of \( \bigwedge^h \mathfrak{g} \) are called \( h \)-forms. We denote by \( \Omega^h (\Omega^e) \) the vector space of all smooth sections of \( \bigwedge^h \mathfrak{g} \) (of \( \bigwedge^h \mathfrak{g} \), respectively).

The identification of \( \bigwedge^h \mathfrak{g} \) and \( \bigwedge^e \mathfrak{g} \) yields a corresponding identification of the basis \( \Theta^h \) of \( \bigwedge^h \mathfrak{g} \) and \( \Theta^e \) of \( \bigwedge^e \mathfrak{g} \). Then \( \Theta^h_x := \Lambda^k(d\tau_{x^{-1}})\Theta^h_e \) is a basis of \( \bigwedge^h \mathfrak{g}_x \). Notice that the Lie algebra \( \mathfrak{g} \) can be identified with the Lie algebra of the left invariant vector fields on \( \mathbb{G} \equiv \mathbb{R}^n \). Hence, the elements of \( \Theta^h_x \) can be identified with the elements of \( \Theta^h \) evaluated at the point \( x \). Through all this paper, we make systematic use of these identifications, interchanging the roles of left invariant vector fields and elements of \( \bigwedge^h \mathfrak{g} \).

Keeping in mind the decomposition (17), we can define in the same way several fiber bundles over \( \mathbb{G} \) (that we still denote with the same symbol \( \bigwedge^{h,p} \mathfrak{g} \)), by setting \( \bigwedge^e \mathfrak{g} := \bigwedge^{h,p} \mathfrak{g} \) and \( \bigwedge^h \mathfrak{g} := \Lambda^k(d\tau_{x^{-1}}) \bigwedge^{h,p} \mathfrak{g} \). Clearly, all previous arguments related to the basis \( \Theta^h \) can be repeated for the basis \( \Theta^{h,p} \).

**Lemma 2.7.** The fiber \( \bigwedge^h \mathfrak{g}_x \) (and hence the fiber \( \bigwedge^{h,p} \mathfrak{g}_x \)) can be endowed with a natural scalar product \( \langle \cdot, \cdot \rangle_x \) by the identity

\[ \langle \alpha, \beta \rangle_x := \langle \Lambda^h d\tau_x(\alpha), \Lambda^h d\tau_x(\beta) \rangle_e. \]

If \( x, y \in \mathbb{G} \), then

\[ \Lambda^h d\tau_{y^{-1}} : \bigwedge^h_{x} \mathfrak{g} \rightarrow \bigwedge^h_{y x} \mathfrak{g} \]

is an isometry onto.

As customary, if \( f : \mathbb{G} \rightarrow \mathbb{G} \) is an isomorphism, then the pull-back of a form \( \omega \in \Omega^h \) is defined by

\[ f^# \omega(x) := (\Lambda^h(df_x))\omega(f(x)). \]

It is easy to see that \( (f^{-1})^#(f^# \omega) = \omega \).
We denote by $\Omega^{h,p}$ the vector space of all smooth $h$–forms in $G$ of pure weight $p$, i.e. the space of all smooth sections of $\bigwedge^h \otimes^p g$. We have

\begin{equation}
\Omega^h = \bigoplus_{p=N^h_{\text{min}}}^{N^h_{\text{max}}} \Omega^{h,p}.
\end{equation}

**Lemma 2.8.** We have $d(\bigwedge^h \otimes^p g) = \bigwedge^{h+1} \otimes^p g$, i.e., if $\alpha \in \bigwedge^h \otimes^p g$ is a left invariant $h$–form of weight $p$, then $w(d\alpha) = w(\alpha)$.

**Proof.** See [25], Section 2.1. \qed

Let now $\alpha \in \Omega^{h,p}$ be a (say) smooth form of pure weight $p$. We can write

$$\alpha = \sum_{\theta^h_i \in \Theta^h,p} \alpha_i \theta^h_i,$$

with $\alpha_i \in \mathcal{E}(G)$. Then

$$d\alpha = \sum_{\theta^h_i \in \Theta^h,p} \sum_j (X_j \alpha_i) \theta^h_i \wedge \theta^h_j + \sum_{\theta^h_i \in \Theta^h,p} \alpha_i d\theta^h_i.$$

Hence we can write

$$d = d_0 + d_1 + \cdots + d_\kappa,$$

where

$$d_0 \alpha = \sum_{\theta^h_i \in \Theta^h,p} \alpha_i d\theta^h_i$$

does not increase the weight,

$$d_1 \alpha = \sum_{\theta^h_i \in \Theta^h,p} \sum_{j=1}^m (X_j \alpha_i) \theta^h_j \wedge \theta^h_i$$

increases the weight of 1, and, more generally,

$$d_k \alpha = \sum_{\theta^h_i \in \Theta^h,p} \sum_{w(\theta_j) = k} (X_j \alpha_i) \theta^h_j \wedge \theta^h_i \quad k = 1, \ldots, \kappa.$$

In particular, $d_0$ is an algebraic operator, in the sense that its action can be identified at any point with the action of an operator on $\bigwedge^h \otimes^p g$ (that we denote again by $d_0$) through the formula

$$(d_0 \alpha)(x) = \sum_{\theta^h_i \in \Theta^h,p} \alpha_i(x) d\theta^h_i = \sum_{\theta^h_i \in \Theta^h,p} \alpha_i(x) d_0 \theta^h_i,$$

by Lemma 2.8. Using the canonical orthonormal system $\Theta^h$, we have a canonical isomorphism $i^h_\Theta$ from $\bigwedge^h \otimes^p g$ onto $\mathbb{R}^{\dim} \bigwedge^h \otimes^p g$. The map $M_h : \mathbb{R}^{\dim} \bigwedge^h \otimes^p \to \mathbb{R}^{\dim} \bigwedge^{h+1} \otimes^p g$ makes the following diagram commutative

$$\begin{array}{ccc}
\mathbb{R}^{\dim} \bigwedge^h \otimes^p g & \xrightarrow{M_h} & \mathbb{R}^{\dim} \bigwedge^{h+1} \otimes^p g \\
\bigwedge^h \otimes^p g & \xrightarrow{i^h_\Theta} & \bigwedge^{h+1} \otimes^p g \\
\bigwedge^{h+1} \otimes^p g & \xrightarrow{(i^h_\Theta)^{-1}} & \bigwedge^h \otimes^p g
\end{array}$$

Because of our choice of the order of the elements of $\Theta^h$, the matrix associated with $M_h$ (that we still denote by $M_h$) is a block matrix, as well as its
transposed. More precisely, the entries of $M_h$ are all 0 except at most for those that belong to groups of rows and columns “of the same weight”.

We stress that all the construction of $M_h$ is left invariant, and hence $M_h$ has constant entries.

Analogously, $\delta_0$, the $L^2$–adjoint of $d_0$ in $\Omega^*$ defined by

$$\int \langle d_0 \alpha, \beta \rangle \, dV = \int \langle \alpha, \delta_0 \beta \rangle \, dV$$

for all compactly supported smooth forms $\alpha \in \Omega^h$ and $\beta \in \Omega^{h+1}$, is again an algebraic operator preserving the weight. Indeed, it can be written as

$$\delta_0 \beta (x) = (i_{\Theta^h_x})^{-1}(^t M_h) i_{\Theta^{h+1}_x} \beta (x).$$

Again, its matrix $^t M_h$ is a block matrix.

**Definition 2.9.** If $0 \leq h \leq n$ we set

$$E^h_0 := \ker d_0 \cap \ker \delta_0 = \ker d_0 \cap (\text{Im } d_0)^\perp \subset \Omega^h,$$

or, in coordinates,

$$E^h_0 = \{ \alpha \in \Omega^h ; i_{\Theta^h_x} \alpha (x) \in \ker M_h \cap \ker M_{h-1} \text{ for all } x \in \mathbb{G} \}.$$

Since the construction of $E^h_0$ is left invariant, this space of forms can be viewed as the space of sections of a fiber bundle, generated by left translation and still denoted by $E^h_0$.

We denote by $N^\min_h$ and $N^\max_h$ the minimum and the maximum, respectively, of the weights of forms in $E^h_0$.

If we set $E^{h,p}_0 := E^h_0 \cap \Omega^{h,p}$, then

$$E^h_0 = \bigoplus_{p = N^\min_h}^{N^\max_h} E^{h,p}_0.$$

Indeed, if $\alpha \in E^h_0$, by (18), we can write

$$\alpha = \sum_{p = N^\min_h}^{N^\max_h} \alpha_p,$$

with $\alpha_p \in \Omega^{h,p}$ for all $p$. By definition,

$$0 = d_0 \alpha = \sum_{p = N^\min_h}^{N^\max_h} d_0 \alpha_p.$$

But $w(d_0 \alpha_p) \neq w(d_0 \alpha_q)$ for $p \neq q$, and hence the $d_0 \alpha_p$’s are linear independent and therefore they are all 0. Analogously, $\delta_0 \alpha_p = 0$ for all $p$, and the assertion follows.

We denote by $\Pi^{h,p}_E$ the orthogonal projection of $\Omega^h$ on $E^{h,p}_0$.

We notice that also the space of forms $E^{h,p}_0$ can be viewed as the space of smooth sections of a suitable fiber bundle generated by left translations, that we still denote by $E^{h,p}_0$. 

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As customary, if $\Omega \subset G$ is an open set, we denote by $E(\Omega, E_0^h)$ the space of smooth sections of $E_0^h$. The spaces $D(\Omega, E_0^h)$ and $S(G, E_0^h)$ are defined analogously.

Since both $E_0^{h,p}$ and $E_0^h$ are left invariant as $\bigwedge^h g$, they are subbundles of $\bigwedge^h g$ and inherit the scalar product on the fibers.

In particular, we can obtain a left invariant orthonormal basis $\Xi^h_0 = \{\xi_j\}$ of $E_0^h$ such that

$$\Xi^h_0 = \bigcup_{p=M^\text{max}_h}^{M^\text{min}_h} \Xi^{h,p}_0,$$

where $\Xi^{h,p}_0 := \Xi^h \cap \bigwedge^{h,p} g$ is a left invariant orthonormal basis of $E_0^{h,p}$. All the elements of $\Xi^{h,p}_0$ have pure weight $p$. Without loss of generality, the indices $j$ of $\Xi^h_0 = \{\xi_j\}$ are ordered once for all in increasing way with respect to the weight of the corresponding element of the basis.

Correspondingly, the set of indices $\{1, 2, \ldots, \dim E_0^h\}$ can be written as the union of finite sets (possibly empty) of indices

$$\{1, 2, \ldots, \dim E_0^h\} = \bigcup_{p=N^\text{min}_h}^{N^\text{max}_h} I^h_{0,p},$$

where

$$j \in I^h_{0,p} \text{ if and only if } \xi^h_j \in \Xi^{h,p}_0.$$

Without loss of generality, we can take

$$\Xi^1_0 = \Xi^{1,1}_0 := \Theta^{1,1}.$$ 

Once the basis $\Theta^h_0$ is chosen, the spaces $E(\Omega, E_0^h)$, $D(\Omega, E_0^h)$, $S(G, E_0^h)$ can be identified with $E(\Omega)^{\dim E_0^h}$, $D(\Omega)^{\dim E_0^h}$, $S(G)^{\dim E_0^h}$, respectively.

**Proposition 2.10.** ([25]) If $0 \leq h \leq n$ and $*$ denote the Hodge duality (see Definition 2.3), then

$$*E_0^h = E_0^{n-h}.$$ 

By a simple linear algebra argument we can prove the following lemma.

**Lemma 2.11.** If $\beta \in \Omega^{h+1}$, then there exists a unique $\alpha \in \Omega^h \cap (\ker d_0)^\perp$ such that

$$\delta_0 d_0 \alpha = \delta_0 \beta.$$ 

We set $\alpha := d_0^{-1} \beta$.

In particular

$$\alpha = d_0^{-1} \beta \text{ if and only if } d_0 \alpha - \beta \in \ker \delta_0.$$ 

Since $d_0^{-1} d_0 = \text{Id}$ on $R(d_0^{-1})$, we can write $d_0^{-1} d = \text{Id} + D$, where $D$ is a differential operator that increases the weight. Clearly, $D : R(d_0^{-1}) \rightarrow R(d_0^{-1})$. As a consequence of the nilpotency of $G$, $D^k = 0$ for $k$ large enough, and the following result holds.
Lemma 2.12 ([25]). The map $d_0^{-1}d$ induces an isomorphism from $R(d_0^{-1})$ to itself. In addition, there exist a differential operator
\[
P = \sum_{k=1}^{N} (-1)^k D^k, \quad N \in \mathbb{N} \text{ suitable},
\]
such that
\[
P d_0^{-1} d = d_0^{-1} d P = \text{Id}_{R(d_0^{-1})}.
\]
We set $Q := P d_0^{-1}$.

Remark 2.13. If $\alpha$ has pure weight $k$, then $P \alpha$ is a sum of forms of pure weight greater or equal to $k$.

We state now the following key results. Some examples will be discussed in detail in Appendix B.

Theorem 2.14 ([25]). There exists a differential operator $d_c : E_0^h \rightarrow E_0^{h+1}$ such that
\[
i) \quad d_c^2 = 0;
\]
\[
ii) \quad \text{the complex } E_0 := (E_0^*, d_c) \text{ is exact;}
\]
\[
iii) \quad \text{the differential } d_c \text{ acting on } h\text{-forms can be identified, with respect to the bases } \Xi_0^h \text{ and } \Xi_0^{h+1}, \text{ with a matrix-valued differential operator } L^h := \left( L^h_{i,j} \right). \text{ If } j \in I_{0,p}^h \text{ and } i \in I_{0,q}^{h+1}, \text{ then the } L^h_{i,j} \text{'s are homogeneous left invariant differential operator of order } q - p \geq 1 \text{ in the horizontal derivatives, and } L^h_{i,j} = 0 \text{ if } j \in I_{0,p}^h \text{ and } i \in I_{0,q}^{h+1}, \text{ with } q - p < 1.
\]

In particular, if $h = 0$ and $f \in E_0^0 = \mathcal{E}(G)$, then $d_c f = \sum_{i=1}^{m} (X_i f) \theta^1_i$ is the horizontal differential of $f$.

The proof of Theorem 2.14 relies on the following result.

Theorem 2.15 ([25]). The de Rham complex $(\Omega^*, d)$ splits in the direct sum of two sub-complexes $(E^*, d)$ and $(F^*, d)$, with
\[
E := \ker d_0^{-1} \cap \ker (d_0^{-1} d) \quad \text{and} \quad F := R(d_0^{-1}) + R(dd_0^{-1}),
\]
such that
\[
i) \quad \text{The projection } \Pi_E \text{ on } E \text{ along } F \text{ is given by } \Pi_E = \text{Id} - Q d - d Q.
\]
\[
ii) \quad \text{If } \Pi_{E_0} \text{ is the orthogonal projection from } \Omega^* \text{ on } E_0^*, \text{ then } \Pi_{E_0} \Pi_E \Pi_{E_0} = \Pi_{E_0} \text{ and } \Pi_E \Pi_{E_0} \Pi_E = \Pi_E.
\]
\[
iii) \quad d_c = \Pi_{E_0} d \Pi_E.
\]
\[
iv) \quad *E = F^⊥.
\]

Remark 2.16. By Theorem 2.15, i), we have
\[
(21) \quad d \Pi_E = \Pi_E d.
\]
Moreover, by Theorem 2.15, iv), if $\alpha \in \Omega^h$ and $\beta \in \Omega^{n-h}$ with $0 \leq h \leq n$, we have
\[
(22) \quad \alpha \wedge (\Pi_E \beta) = (\Pi_E \alpha) \wedge (\Pi_E \beta) = (\Pi_E \alpha) \wedge \beta.
\]
Finally, if $\alpha \in \Omega^h$ and $\beta \in E_0^{n-h}$ with $0 \leq h \leq n$, we have
\[
(23) \quad \alpha \wedge \beta = (\Pi_{E_0} \alpha) \wedge \beta.
\]
Proposition 2.17 ([25], formula (7)). For any \( \alpha \in E_0^{h,p} \), if we denote by \((\Pi_E \alpha)_j\) the component of \(\Pi_E \alpha\) of weight \(j\) (that is necessarily greater or equal than \(p\), by Remark 2.13), then

\[
(\Pi_E \alpha)_p = \alpha
\]

(24)

\[(\Pi_E \alpha)_{p+k+1} = -d_0^{-1} \left( \sum_{1 \leq \ell \leq k+1} d_{\ell}(\Pi_E \alpha)_{p+k+1-\ell} \right).\]

Remark 2.18. In fact, we can notice that, if \( \alpha \in E_0^{h,p} \), then \(d_c \alpha\) has no components of weight \(j = p\). Indeed,

\[\Pi_E \alpha = \alpha + \text{terms of weight greater than } p.\]

Thus

\[d \Pi_E \alpha = d_0 \alpha + \text{terms of weight greater than } p.\]

But \(d_0 \alpha = 0\) by the very definition of \(E_0^{h,p}\), and the assertion follows.

Definition 2.19. If \( \Omega \subset \mathbb{G} \) is an open set, we say that \( T \) is a \( h \)-current on \( \Omega \) if \( T \) is a continuous linear functional on \( D' (\Omega, E_0^h) \) endowed with the usual topology. We write \( T \in D' (\Omega, E_0^h) \).

The definition of \( E' (\Omega, E_0^h) \) is given analogously.

Proposition 2.20. If \( \Omega \subset \mathbb{G} \) is an open set, and \( T \in D' (\Omega) \) is a (usual) distribution, then \( T \) can be identified canonically with a \( n \)-current \( \tilde{T} \in D' (\Omega, E_0^n) \) through the formula

\[
\langle \tilde{T} | \alpha \rangle := \langle T | * \alpha \rangle
\]

(25)

for any \( \alpha \in D (\Omega, E_0^n) \). Reciprocally, by (25), any \( n \)-current \( \tilde{T} \) can be identified with an usual distribution \( T \in D' (\Omega) \).

Proof. See [7], Section 17.5, and [1], Proposition 4. \( \square \)

Following [8], 4.1.7, we give the following definition.

Definition 2.21. If \( T \in D' (\Omega, E_0^h) \), and \( \varphi \in E (\Omega, E_0^k) \), with \( 0 \leq k \leq n \), we define \( T \llcorner \varphi \in D' (\Omega, E_0^{n-k}) \) by the identity

\[
\langle T \llcorner \varphi | \alpha \rangle := \langle T | \alpha \wedge \varphi \rangle
\]

for any \( \alpha \in D (\Omega, E_0^{n-k}) \).

The following result is taken from [1], Propositions 5 and 6, and Definition 10, but we refer also to [7], Sections 17.3 17.4 and 17.5.

Proposition 2.22. Let \( \Omega \subset \mathbb{G} \) be an open set. If \( 1 \leq h \leq n \), \( E_0^h = \{ \xi_1^h, \ldots, \xi_{\dim E_0^h}^h \} \) is a left invariant basis of \( E_0^h \) and \( T \in D' (\Omega, E_0^h) \), then

i) there exist (uniquely determined) \( T_1, \ldots, T_{\dim E_0^h} \in D' (\Omega) \) such that we can write

\[
T = \sum_j T_j \llcorner (* \xi_j^h);
\]
ii) if $\alpha \in E(\Omega, E_h^0)$, then $\alpha$ can be identified canonically with a $h$-current $T_\alpha$ through the formula

$$\langle T_\alpha | \beta \rangle := \int_\Omega \ast \alpha \wedge \beta$$

for any $\beta \in D(\Omega, E_h^0)$. Moreover, if $\alpha = \sum_j \alpha_j \xi^j_h$ then

$$T_\alpha = \sum_j \tilde{\alpha}_j \xi^j_h$$

for any $\beta \in D(\Omega, E_h^0)$. Moreover, if $\alpha = \sum_j \alpha_j \xi^j_h$ then

$$T_\alpha = \sum_j \tilde{\alpha}_j \xi^j_h$$

for any $\beta \in D(\Omega, E_h^0)$ (in fact, we choose $\beta = \sum_j T_j \xi^j_h$).

The notion of convolution can be extended by duality to currents.

**Definition 2.23.** Let $\varphi \in D(G)$ and $T \in E'(G, E_h^0)$ be given, and denote by $\gamma \varphi$ the function defined by $\gamma \varphi(p) := \varphi(p^{-1})$. Then we set

$$\langle \varphi \ast T | \alpha \rangle := \langle T | \gamma \varphi \ast \alpha \rangle$$

for any $\alpha \in D(G, E_h^0)$.

We need a few definitions. For all our notations related to Rumin’s complex, we refer to Appendix B. We set

$$I^h_0 := \{ p : I^h_{0,p} \neq \emptyset \} \quad \text{and} \quad |I^h_0| = \text{card} I^h_0.$$  

Let

$$m = (m_{N^h_{\min}}, \ldots, m_{N^h_{\max}})$$

be a $|I^h_0|$-dimensional vector where the components are indexed by the elements of $I^h_0$ (i.e. by the possible weights) taken in increasing order. We stress that, since weights $p$ such that $I^h_{0,p} = \emptyset$ can exist, some consecutive indices in $m$ can be missed. In the sequel we shall say that $m$ is a $h$-vector weight. We say that $m \geq n$ if $m_p \geq n_p$ for all $p \in I^h_0$. We say also that $m > n$ if $m_p > n_p$ for all $p \in I^h_0$. Finally, if $m_0$ is a real number, we identify $m_0$ with the $h$-vector weight $m_0 = (m_0, \ldots, m_0)$. In particular, we set $m - m_0 := (m_{N^h_{\min}} - m_0, \ldots, m_{N^h_{\max}} - m_0)$.

**Definition 2.24.** A special $h$-vector weight that we shall use in the sequel is the $h$-vector weight $N_h = (m_{N^h_{\min}}, \ldots, m_{N^h_{\max}})$ with

$$m_p = p \quad \text{for all} \ p \in I^h_0.$$ 

If all $h$-forms have pure weight $N_h$, i.e. if $N^h_{\min} = N^h_{\max} := N_h$, then a $h$-vector weight has only one component, i.e. $m = (m_{N_h})$. 

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3. Function spaces

Through the next sections, we use notations and results contained in Appendix A and basically relying on the pseudodifferential operators and their calculus of Christ, Geller, Glowacki & Polin ([5]). Briefly, we refer to their operators as to CGGP-operators, and we call CGGP-calculus the associated calculus.

Let \( \{X_1, \ldots, X_m\} \) be the fixed basis of the horizontal layer \( g_1 \) of \( g \) chosen in Section 2. We denote by \( \Delta_G \) the nonnegative horizontal sublaplacian
\[
\Delta_G := -\sum_{j=1}^{m} X_j^2.
\]

If \( 1 < s < \infty \) and \( a \in \mathbb{C} \), we define \( \Delta_G^a \) in \( L^s(G) \) following [9]. If in addition \( m \geq 0 \), again as in [9], we denote by \( W_{m,s}^G(G) \) the domain of the realization of \( \Delta_G^{m/2} \) in \( L^s(G) \) endowed with the graph norm. In fact, since \( s \in (1, \infty) \) is fixed through all the paper, to avoid cumbersome notations, we do not stress the explicit dependence on \( s \) of the fractional powers \( \Delta_G^{m/2} \) and of its domain.

Proposition 3.1. The operators \( \Delta_G^{m/2} \) are left invariant on \( W_{m,s}^G(G) \).

Proof. The proof is straightforward, keeping in mind the form of \( \Delta_G^{m/2} \) ([9], p.181), and the representation of the heat semigroup associated with \( \Delta_G \) ([9], Theorem 3.1 (i)). □

We remind that

Proposition 3.2 ([9], Corollary 4.13). If \( 1 < s < \infty \) and \( m \in \mathbb{N} \), then the space \( W_{m,s}^G(G) \) coincides with the space of all \( u \in L^s(G) \) such that
\[
X^I u \in L^s(G) \quad \text{for all multi-index } I \text{ with } d(I) = m,
\]
endowed with the natural norm.

Proposition 3.3 ([9], Corollary 4.14). If \( 1 < s < \infty \) and \( m \geq 0 \), then the space \( W_{m,s}^G(G) \) is independent of the choice of \( X_1, \ldots, X_m \).

Proposition 3.4. If \( 1 < s < \infty \) and \( m \geq 0 \), then \( \mathcal{S}(G) \) and \( \mathcal{D}(G) \) are dense subspaces of \( W_{m,s}^G(G) \).

Proof. The density of \( \mathcal{D}(G) \) is proved in [9], Theorem 4.5. If \( m \in \mathbb{N} \cup \{0\} \), by Proposition 3.2, \( \mathcal{S}(G) \subset W_{m,s}^G(G) \), since the vector fields \( X_1, \ldots, X_m \) have polynomial coefficients (see Proposition 2.2). Thus, by [9], Proposition 4.2, \( \mathcal{S}(G) \subset W_{m,s}^G(G) \) for \( m \geq 0 \). Moreover, since \( \mathcal{D}(G) \) is a dense subspace of \( W_{m,s}^G(G) \), the assertion follows. □

Definition 3.5. Let \( m \geq 0, 1 < s < \infty \) be fixed indices. Let \( \Omega \subset G \) be a given open set with \( \mathcal{L}^n(\partial \Omega) = 0 \) (from now on, even if not explicitly stated, we shall assume this regularity property whenever an open set is meant to localize a statement). We denote by \( W_{m,s}^G(\Omega) \) the completion in \( W_{m,s}^G(G) \) of \( \mathcal{D}(\Omega) \). More precisely, denote by \( v \rightarrow v|_{\Omega} \) the restriction operator to \( \Omega \); we say that \( u \) belongs to \( W_{m,s}^G(\Omega) \) if there exists a sequence of test functions \( (u_k)_{k \in \mathbb{N}} \) in \( \mathcal{D}(\Omega) \) and \( U \in W_{m,s}^G(G) \), such that \( u_k \rightarrow U \) in
\(W_{m,s}^{m,s}(\mathbb{G})\) and \(u = r_{\Omega}U\). On the other hand, since in particular \(u_k \to U\) in \(L^s(\mathbb{G})\), necessarily \(U \equiv 0\) outside of \(\Omega\). Therefore, if \(u = r_{\Omega}U_1 = r_{\Omega}U_2\) with \(U_1, U_2\) both belonging to the completion in \(W_{m,s}^{m,s}(\mathbb{G})\) of \(D(\Omega)\), then \(U_1 \equiv U_2\), so that, without loss of generality, we can set
\[
\|u\|_{\hat{W}_{m,s}^{m,s}(\Omega)} := \|p_0(u)\|_{W_{m,s}^{m,s}(\mathbb{G})},
\]
where \(p_0(u)\) denotes the continuation of \(u\) by zero outside of \(\Omega\).

It is well known that \(W^{1,s}_{1,\text{loc}}(\mathbb{G})\) is continuously imbedded in \(W^{1/(\kappa+1)}_{\text{loc}}(\mathbb{G})\) (see [22]); thus, by classical Rellich theorem and interpolation arguments ([9], Theorem 4.7 and [27], 1.16.4, Theorem 1), we have:

**Lemma 3.6.** Let \(\Omega \subset \mathbb{G}\) be a bounded open set. If \(s > 1\), and \(m > 0\), then
\[\hat{W}_{m,s}^{m,s}(\Omega)\] is compactly embedded in \(L^s(\Omega)\).

**Proposition 3.7.** If \(m \geq 0\), \(1 < s < \infty\) and \(\Omega \subset \mathbb{G}\) is a bounded open set, then
\[
\|u\|_{\hat{W}_{m,s}^{m,s}(\Omega)} \approx \|\Delta_{G,m/2}p_0(u)\|_{L^s(\mathbb{G})}
\]
when \(u \in \hat{W}_{m,s}^{m,s}(\Omega)\) and \(p_0(u)\) denotes its continuation by zero outside of \(\Omega\).

**Proof.** By Definition 3.5,
\[
\|u\|_{\hat{W}_{m,s}^{m,s}(\Omega)} = \|p_0(u)\|_{W_{m,s}(\mathbb{G})} \geq \|\Delta_{G,m/2}p_0(u)\|_{L^s(\mathbb{G})},
\]
so that we have only to prove the reverse estimate.

We want to show preliminarily that the map \(u \to \Delta_{G,m/2}p_0(u)\) from \(\hat{W}_{m,s}^{m,s}(\Omega)\) to \(L^s(\mathbb{G})\) is injective. Let \(u \in \hat{W}_{m,s}^{m,s}(\Omega)\) be such that \(\Delta_{G,m/2}p_0(u) = 0\).

If \((\rho_\varepsilon)_{\varepsilon > 0}\) are group mollifiers, by the left invariance of \(\Delta_{G,m/2}\), we have \(\rho_\varepsilon * p_0(u) \in D(\mathbb{G})\) and \(\Delta_{G,m/2}(\rho_\varepsilon * p_0(u)) = 0\) for \(\varepsilon > 0\). By [9], Theorem 3.15 (iii), keeping in mind that \(D(\mathbb{G}) \subset \text{Dom} (\Delta_{G,m/2})\) for all \(\alpha \geq 0\), if \(N\) is an integer number such that \(N \geq m/2\), then \(\Delta_{G,N}(\rho_\varepsilon * p_0(u)) = \Delta_{G,N-m/2}(\rho_\varepsilon * (\rho_{\varepsilon} * p_0(u))) = 0\), so that \(\rho_{\varepsilon} * p_0(u) = 0\), e.g. by Bony’s maximum principle. Then, taking the limit as \(\varepsilon \to 0\), \(p_0(u) = 0\), and eventually \(u = 0\).

We can achieve now the proof by using a simple form of the following Peetre-Tartar lemma (see, e.g., [6], p. 126):

**Lemma 3.8** (Peetre–Tartar). Let \(V, V_1, V_2, W\) be Banach spaces, and let \(A_i \in \mathcal{L}(V, V_i)\) be continuous linear maps for \(i = 1, 2\), the map \(A_1\) being compact. Suppose there exists \(c_0 > 0\) such that
\[
\|v\|_V \leq c_0(\|A_1v\|_{V_1} + \|A_2v\|_{V_2})
\]
for any \(v \in V\). In addition, let \(L \in \mathcal{L}(V, W)\) be a continuous linear map such that
\[
L|_{\ker A_2} \equiv 0.
\]
Then there exists \(C > 0\) such that
\[
\|Lv\|_W \leq C\|A_2v\|_{V_2}
\]
for any \(v \in V\).
For our purposes, we choose $V = \tilde{W}_{G}^{m,s}(\Omega)$, $V_1 = V_2 = L^s(\mathcal{G})$, $W = W^{m,s}(\mathcal{G})$, $A_1 = p_0$, $A_2 = \Delta_G^{m/2} \circ p_0$, $L = p_0$. Indeed, $A_1 := p_0$ is a compact map from $\tilde{W}_{G}^{m,s}(\Omega)$ to $L^s(\mathcal{G})$, by Lemma 3.6. On the other hand, we have already pointed out in Definition 3.5 that $p_0(u) \in W^{m,s}(\mathcal{G})$, so that $\Delta_G^{m/2} p_0(u) \in L^s(\mathcal{G})$, and $\|\Delta_G^{m/2} p_0(u)\|_{L^s(\mathcal{G})} \leq \|p_0(u)\|_{W^{m,s}(\mathcal{G})} := \|u\|_{\tilde{W}_{G}^{m,s}(\Omega)}$ (again by Definition 3.5). Thus $A_2 := \Delta_G^{m/2} \circ p_0 : \tilde{W}_{G}^{m,s}(\Omega) \to L^s(\mathcal{G})$ continuously. The same argument shows that (27) holds. On the other hand, we have shown that ker $A_2 = \{0\}$, so that (28) holds.

Then (29) reads as

$$\|u\|_{\tilde{W}_{G}^{m,s}(\Omega)} = \|p_0(u)\|_{W^{m,s}(\mathcal{G})} \leq C \|\Delta_G^{m/2} p_0(u)\|_{L^s(\mathcal{G})},$$
achieving the proof of the proposition. \qed

**Lemma 3.9.** If $m > 0$ let $P_m \in K^{-m Q}$ be the kernel defined in Theorem 6.16 and Remark 6.17. If $\Omega \subset \subset \mathcal{G}$ is an open set, $R > R_0(s, \mathcal{G}, m, \Omega)$ is sufficiently large, and $u \in D(\mathcal{G})$, then

$$\|u\|_{\tilde{W}_{G}^{m,s}(\Omega)} \approx \|O((P_m)R)u\|_{L^s(\mathcal{G})} = \|\Delta_G^{m/2} u\|_{L^s(\mathcal{G})},$$
with equivalence constants depending on $s, \mathcal{G}, m, \Omega$.

**Proof.** By Proposition 3.7, there exists $c_\Omega > 0$ such that (keeping in mind that we can think $p_0(u) = u$)

$$\|\Delta_G^{m/2} u\|_{L^s(\mathcal{G})} \leq \|u\|_{\tilde{W}_{G}^{m,s}(\Omega)} \leq c_\Omega \|\Delta_G^{m/2} u\|_{L^s(\mathcal{G})}.$$

By Remark 6.17, we have

$$\Delta_G^{m/2} u = O((P_m)R)u + Su,$$
where $Su = u \ast (1 - \psi_R)P_m$. Hence

$$\|\Delta_G^{m/2} u\|_{L^s(\mathcal{G})} \leq \|O((P_m)R)u\|_{L^s(\mathcal{G})} + \|u \ast (1 - \psi_R)P_m\|_{L^s(\mathcal{G})}.$$

On the other hand, by [9], Proposition 1.10, and a standard argument (see e.g. [15], [16])

$$\|u \ast (1 - \psi_R)P_m\|_{L^s(\mathcal{G})} \leq C_s \|u\|_{L^s(\mathcal{G})} \cdot \|(1 - \psi_R)P_m\|_{L^1(\mathcal{G})} \leq C(s, \mathcal{G}, m)R^{-m} \|u\|_{L^s(\mathcal{G})} \leq C(s, \mathcal{G}, m)R^{-m} c_\Omega \|\Delta_G^{m/2} u\|_{L^s(\mathcal{G})} \leq \frac{1}{2} \|\Delta_G^{m/2} u\|_{L^s(\mathcal{G})},$$

provided $R > R_0(s, \mathcal{G}, m, \Omega)$. Therefore

$$\|\Delta_G^{m/2} u\|_{L^s(\mathcal{G})} \leq 2\|O((P_m)R)u\|_{L^s(\mathcal{G})}$$

and hence

$$\|u\|_{\tilde{W}_{G}^{m,s}(\Omega)} \leq 2c_\Omega \|O((P_m)R)u\|_{L^s(\mathcal{G})}.$$

Conversely,

$$\|O((P_m)R)u\|_{L^s(\mathcal{G})}$$

$$\leq \|\Delta_G^{m/2} u\|_{L^s(\mathcal{G})} + \|u \ast (1 - \psi_R)P_m\|_{L^s(\mathcal{G})} \leq \frac{3}{2} \|\Delta_G^{m/2} u\|_{L^s(\mathcal{G})} \leq \frac{3}{2} \|u\|_{\tilde{W}_{G}^{m,s}(\Omega)}.$$
This achieves the proof of the lemma.

**Definition 3.10.** Let $\Omega \subset \mathbb{G}$ be an open set. If $m \geq 0$ and $1 < s < \infty$, $W_{\mathbb{G}}^{-m,s}(\Omega)$ is the dual space of $\overset{\circ}{W}_{\mathbb{G}}^{k,s'}(\Omega)$, where $1/s + 1/s' = 1$. It is well known that, if $m \in \mathbb{N}$ and $\Omega$ is bounded, then

$$W_{\mathbb{G}}^{-m,s}(\Omega) = \{ \sum_{d(I)=k} X^I f_I, f_I \in L^s(\Omega) \text{ for any } I \text{ such that } d(I) = k \},$$

and

$$\|u\|_{W_{\mathbb{G}}^{-m,s}(\Omega)} \approx \inf \{ \sum_{I} \|f_I\|_{L^s(\Omega)} : d(I) = k, \sum_{d(I)=k} X^I f_I = u \}.$$

**Proposition 3.11.** If $1 < s < \infty$ and $m, m' \geq 0$, $m' < m$, then

$$W_{\mathbb{G}}^{m,s}(\mathbb{G}) \hookrightarrow W_{\mathbb{G}}^{m',s}(\mathbb{G}) \text{ and } W_{\mathbb{G}}^{-m,s}(\mathbb{G}) \hookrightarrow W_{\mathbb{G}}^{-m',s}(\mathbb{G})$$

algebraically and topologically.

In addition, if $\Omega$ is a bounded open set, $1 < s < \infty$ and $m, m' \geq 0$, $m' < m$, then

$$\overset{\circ}{W}_{\mathbb{G}}^{m,s}(\Omega) \text{ is compactly embedded in } W_{\mathbb{G}}^{m',s}(\Omega)$$

and

$$W_{\mathbb{G}}^{-m',s}(\Omega) \text{ is compactly embedded in } W_{\mathbb{G}}^{-m,s}(\Omega).$$

**Proof.** The first assertion is nothing but [9], Proposition 4.2. As for the second assertion, take first $R > 0$, and let $\Omega_0$ be a sufficiently large bounded open neighborhood of $\overline{\Omega}$. If $u \in \overset{\circ}{W}_{\mathbb{G}}^{m,s}(\Omega)$, by Lemma 6.18, we can write

$$u = \Delta_{\mathbb{G},R}^{m'/2} \circ \Delta_{\mathbb{G},R}^{m'/2} u + \varphi Su,$$

where $\varphi \in \mathcal{D}(\Omega_0)$ and $S \in \mathcal{OC}^{-\infty}$. By Lemma 6.11, the map $u \rightarrow \varphi Su$ is compact from $\overset{\circ}{W}_{\mathbb{G}}^{m,s}(\Omega)$ to $W_{\mathbb{G}}^{m',s}(\Omega_0)$. As for the first term, the same property follows from Proposition 6.19, Lemma 6.7, and Lemma 3.6.

Finally, the third assertion of the proposition follows by duality. □

**Remark 3.12.** In fact, the compactness result of Proposition 3.11 can be improved as in the Euclidean space (see e.g. [17], Section 1.4.6). For sake of simplicity, let us restrict ourselves to the case $m \in \mathbb{N}$ and $m' = 0$. We have

$$\overset{\circ}{W}_{\mathbb{G}}^{m,s}(\Omega) \text{ is compactly embedded in } L^\sigma(\Omega)$$

and

$$L^\sigma(\Omega) \text{ is compactly embedded in } W_{\mathbb{G}}^{-m,s'}(\Omega),$$

if $s, s'$ and $\sigma, \sigma'$ are Hölder conjugate exponents, provided $\sigma(m - Q/s) + Q > 0$.

**Definition 3.13.** If $m \geq 0$ is a $h$-vector weight, $0 \leq h \leq n$, and $s > 1$, we say that a measurable section $\alpha$ of $E_0^h$, $\alpha := \sum_p \sum_{j \in I_{0,p}} \alpha_j e_j$ belongs to $W_{\mathbb{G}}^{m,s}(\mathbb{G}, E_0^h)$ if, for all $p \in I_0^h$, i.e. for all $p$, $N_0^{\min} \leq p \leq N_0^{\max}$, such that $I_{0,p} \neq \emptyset$,

$$\alpha_j \in W_{\mathbb{G}}^{m_p,s}(\mathbb{G})$$

for all $j \in I_{0,p}$, endowed with the natural norm.
The spaces $W_{G}^{m,s}(Ω, E^h_0)$, where $Ω$ is an open set in $G$, as well as the local spaces $W_{G, loc}^{m,s}(Ω, E^h_0)$ are defined in the obvious way. Since

$$W_{G}^{m,s}(Ω, E^h_0)$$
is isometric to \( \prod_{p∈\mathcal{I}_0^h} (W_{G}^{m,0,s}(G))^\text{card} \mathcal{I}_0^h p, \)

then

- $W_{G}^{m,s}(Ω, E^h_0)$ is a reflexive Banach space (remember $s > 1$);
- $C^0(Ω, E^h_0) ∩ W_{G}^{m,s}(Ω, E^h_0)$ is dense in $W_{G}^{m,s}(Ω, E^h_0)$.

The spaces $W_0^{m,s}(Ω, E^h_0)$ are defined in the obvious way.

We can define and characterize the dual spaces of Sobolev spaces of forms.

**Proposition 3.14.** If $1 < s < ∞$, $1/s + 1/s' = 1$, $0 ≤ h ≤ n$, $m$ is a $h$–vector weight, and $Ω ⊂ G$ is a bounded open set, then the dual space \((W_{G, loc}^{m,s'}(Ω, E^h_0))^*\) coincides with the set of all currents $T ∈ D'(Ω, E^h_0)$ of the form (with the notations of Proposition 2.20)

$$T = \sum_{p} \sum_{j∈I_0^h} \tilde{T}_j \langle *ξ^h_j \rangle$$

with $T_j ∈ W_{G}^{-m,s'}(Ω)$ for all $j ∈ I_0^h$ and for $p ∈ \mathcal{I}_0^h$. The action of $T$ on the form $α = \sum_p \sum_{j∈I_0^h} α_j ξ^h_j ∈ W_{G, loc}^{m,s'}(Ω, E^h_0)$ is given by the identity

$$T(α) = \sum_{p} \sum_{j∈I_0^h} \langle T_j | α_j \rangle.$$  

In particular, it is natural to set

$$W_{G}^{-m,s}(Ω, E^h_0) := (W_{G, loc}^{m,s'}(Ω, E^h_0))^*.$$  

Moreover, if $T$ is as in (30)

$$‖T‖_{W_{G}^{-m,s}(Ω, E^h_0)} ≈ \sum_{p} \sum_{j∈I_0^h} ‖T_j‖_{W_{G}^{-m,s'}(Ω)}.$$  

**Proof.** Suppose (30) holds. If $α = \sum_{q} \sum_{i∈I_{0,q}} α_i ξ^h_i$ is smooth and compactly supported in $Ω$, then (keeping in mind that the basis \{ξ^h_i\} is orthonormal, so that $ξ^h_i ∧ *ξ^h_j = δ_{ij} dV$)

$$\langle Σ_p \sum_{j∈I_0^h} \tilde{T}_j \langle *ξ^h_j | α \rangle \rangle = \langle Σ_p \sum_{j∈I_0^h} \sum_{q} \sum_{i∈I_{0,q}} \langle \tilde{T}_j \langle *ξ^h_j | α_i ξ^h_i \rangle \rangle \rangle = \sum_{p} \sum_{j∈I_0^h} \sum_{q} \sum_{i∈I_{0,q}} \langle T_j | α_i (ξ^h_i ∧ *ξ^h_j) \rangle = \sum_{q} \sum_{i∈I_{0,q}} \langle T_i | α_i \rangle.$$  

Thus, clearly, if $T_j ∈ W_{G}^{-m,s'}(Ω)$ for all $i ∈ I_{0,q}$ and for $q ∈ \mathcal{I}_0^h$, then the map $α → \sum_p \sum_{j∈I_0^h} \langle T_j | α_j \rangle$ belongs to \((W_{G, loc}^{m,s'}(Ω, E^h_0))^*\).
Suppose now \( T \in (\tilde{W}_{\tilde{E},0}^{m,s'}(\Omega, E_0^h))^* \). Since \( D(\Omega, E_0^h) \hookrightarrow \tilde{W}_{\tilde{E},0}^{m,s'}(\Omega, E_0^h) \), then \( T \) can be identified with a current that we still denote by \( T \). Thus, by Proposition 2.22, we can write
\[
T = \sum_p \sum_{j \in I_{0,p}^h} \tilde{T}_j \Sigma_j^{\epsilon h}.
\]
If \( i \in I_{0,p}^h \) for some \( p \in I_0^h \) and \( f \in D(\Omega) \), we can consider the map
\[
f \rightarrow \langle T|f\xi_i^h \rangle = \sum_p \sum_{j \in I_{0,p}^h} \langle \tilde{T}_j|f\xi_i^h \wedge (\star \xi_j^h) \rangle = \langle T_i|f \rangle.
\]
Because of the boundedness of \( T \), we get
\[
|\langle T_i|f \rangle| \leq C\|f\xi_i^h\|_{\tilde{W}^{m,s'}(\Omega, E_0^h)} = C\|f\|_{\tilde{W}^{m,s'}(\Omega)}
\]
that yields \( T_i \in W_{G}^{-m,p,s}(\Omega) \). This achieve the proof. \( \square \)

4. HODGE DECOMPOSITION AND COMPENSATED COMPACTNESS

In this section we state and we prove our main results, i.e. a Hodge decomposition theorem for forms in \( E_0^h \) and as a consequence our compensated compactness theorem in \( E_0^h \). Through this section, we assume that \( h \), the degree of the forms we are dealing with, is fixed once and for all, \( 1 \leq h \leq n \), even if it is not mentioned explicitly in the statements.

From now on, we always assume that an orthonormal left invariant basis \( \{ \xi_j^\ell \} \) of \( E_0^\ell \) has been fixed for all \( \ell = 1, \ldots, n \), and therefore pseudodifferential operators acting on intrinsic forms or current and matrix-valued pseudodifferential operators can be identified. We use this identification without referring explicitly to it.

**Theorem 4.1.** Let \( s > 1 \) and \( h = 1, \ldots, n \) be fixed, and suppose \( h \)-forms have pure weight \( N_h \). Let \( \Omega \subset \subset \mathbb{G} \) a given open set, and let \( \alpha^\varepsilon \in L^s(\mathbb{G}, E_0^h) \) and \( E(\mathbb{G}, E_0^h) \) be compactly supported differential \( h \)-forms such that
\[
\alpha^\varepsilon \rightharpoonup \alpha \quad \text{as} \quad \varepsilon \to 0 \quad \text{weakly in} \quad L^s_{\text{loc}}(\mathbb{G}, E_0^h)
\]
and
\[
\{d_c \alpha^\varepsilon\} \quad \text{is pre-compact in} \quad W_{G,\text{loc}}^{-(N_h+1)-N_h,s}(\mathbb{G}, E_0^h).
\]

Then there exist \( h \)-forms \( \omega^\varepsilon \in E_0^h \) and \((h-1)\)-forms \( \psi^\varepsilon \in E_0^{h-1} \) such that

i) \( \omega^\varepsilon \rightharpoonup \omega \quad \text{strongly in} \quad L^s_{\text{loc}}(\mathbb{G}, E_0^h) \);

ii) \( \psi^\varepsilon \rightharpoonup \psi \quad \text{strongly in} \quad L^s_{\text{loc}}(\mathbb{G}, E_0^{h-1}) \);

iii) \( \alpha^\varepsilon = \omega^\varepsilon + d_c \psi^\varepsilon \).

In addition, we can choose \( \omega^\varepsilon \) and \( \psi^\varepsilon \) supported in a fixed suitable neighborhood of \( \Omega \) which are smooth forms if the \( \alpha^\varepsilon \) are also smooth.

**Remark 4.2.** We stress that \( d_c : L^s(\mathbb{G}, E_0^h) \to W_{G}^{-(N_h+1)-N_h,s}(\mathbb{G}, E_0^h) \). Indeed, if \( \alpha = \sum_{j \in I_{0,N_h}^h} \alpha_j \xi_j^h \in L^s(\mathbb{G}, E_0^h) \) and \((d_c \alpha)_i\) is a component of weight \( q \) of \( d_c \alpha \), then (keeping in mind that \( h \)-forms have pure weight \( N_h \))
\[
(d_c \alpha)_i = \sum_j L_{i,j}^h \alpha_j,
\]
where \( L_{i,j}^h \) is a homogeneous differential operator in the
Let now Notice also that By Theorem 6.8(a) in Appendix A, \(E\) belonging to \(L\) with a matrix-valued differential operator \((32)\)

Again the definition is well posed, and \(\delta_c : \mathcal{E}'(B(e, R), E_0^h) \to \mathcal{E}'(B(e, 3R), E_0^h)\).

Analogously, we define the following “0-order codifferential” acting on compactly supported \((h + 1)\)-currents belonging to \(\mathcal{E}'(B(e, R), E_0^{h+1})\):

Again the definition is well posed, and \(\tilde{\delta}_c : \mathcal{E}'(B(e, R), E_0^{h+1}) \to \mathcal{E}'(B(e, 3R), E_0^h)\).

By Theorem 6.8(a) in Appendix A,

Notice also that \(d_c^2 = 0, \, \delta_c^2 = 0 \pmod{\mathcal{O}_c^\infty}\).

Let now \(T = \sum_p \sum_j \in I_0^p \tilde{T}_j \mathcal{L}(\star \xi_j) \in \mathcal{E}'_0(B(e, R))\) be given.

By Theorem 2.14, the differential \(d_c\) acting on \(h\)-forms can be identified with a matrix-valued differential operator \(L_h := (L_i^j)\), where the \(L_i^j\)'s are homogeneous left invariant differential operator of order \(q - p\) if \(j \in I_0^p\) and \(i \in I_0^{h+1}\). Thus, by Definition 6.20, we have

Analogously, if \(T = \sum_q \sum_j \in I_0^{h+1} \tilde{T}_j \mathcal{L}(\star \xi_j) \in \mathcal{E}'(B(e, R), E_0^{h+1})\), then

**Proposition 4.4.** Both \(\tilde{\delta}_c\) and \(\tilde{\delta}_c\) are matrix-valued pseudodifferential operators of the CGGP-calculus, acting respectively on \(\mathcal{E}'(G, E_0^h)\) and \(\mathcal{E}'(G, E_0^{h+1})\). Moreover \(\tilde{\delta}_c \sim P^h := (P_i^j)\), where

(32) \[ P_i^j = P_{q-2} L_i^j P_q \] if \(i \in I_0^{h+1}\) and \(j \in I_0^h\),

and \(\tilde{\delta}_c \sim Q^h := (Q_i^j)\), where

(33) \[ Q_i^j = P_{q-2} (t L_i^j P_{-p}) \] if \(i \in I_0^h\) and \(j \in I_0^{h+1}\).
Proof. Take $i \in I_{0,q}^{h+1}$ and $j \in I_{0,p}^{h}$. Statement (32) follows by proving that
\[
\Delta_{G,R}^{-q/2} L_{i,j}^{h} \Delta_{G,R}^{p/2} \sim P_{-q} \sum (L_{i,j}^{h} P_{p}).
\]
The proof of (33) is analogous. Thus, notice first that, by (55) and Lemma 6.12, the cores of $L_{i,j}^{h} \Delta_{G,R}^{-q/2}$ and $\Delta_{G,R}^{p/2}$ are, respectively, $L_{i,j}^{h} P_{p}$ and $P_{-q}$.
Hence the assertion follows by Theorem 6.8 (c).

Remark 4.5. With Rumin’s notations (see [24], [25]), when acting on $\mathcal{S}_{0}(G, E_{0}^{h})$,
\[
\mathcal{O}_{0}(P^{h}) \equiv d_{c}^{\nabla}.
\]
An analogous assertion hold for $\mathcal{O}_{0}(Q^{h})$.

We set
\[
\Delta_{G,R}^{(0)} := \tilde{d}_{c} d_{c} + \tilde{d}_{c} \delta_{c}.
\]
The following assertion is a straightforward consequence of Theorem 6.8 and Proposition 4.4.

Proposition 4.6. $\Delta_{G,R}^{(0)}$ is a matrix-valued $0$-order pseudodifferential operator of the CGGP-calculus acting on $\mathcal{E}'(\mathbb{G}, E_{0}^{h})$, and
\[
\Delta_{G,R}^{(0)} \sim \Delta_{G}^{(0)} := (\Delta_{G,ij}^{(0)}),
\]
where
\[
\Delta_{G,ij}^{(0)} = \sum_{\ell} \left( Q_{ij}^{\ell} + P_{ij}^{\ell} + P_{ij}^{\ell} Q_{ij}^{\ell} \right).
\]

Remark 4.7. As in Remark 4.5, with the notations of [24], [25], when acting on $\mathcal{S}_{0}(G, E_{0}^{h})$,
\[
\mathcal{O}_{0}(\Delta_{G}^{(0)}) = \mathcal{O}_{0}(Q^{h}) \circ d_{c} \mathcal{O}_{0}(P^{h}) + \mathcal{O}_{0}(P^{h-1}) \circ \delta_{c} \mathcal{O}_{0}(Q^{h-1})
= \delta_{c}^{\nabla} d_{c}^{\nabla} + d_{c}^{\nabla} \delta_{c}^{\nabla} = \Box_{d_{c}}.
\]

Theorem 4.8. For any $R > 0$ there exists a (matrix-valued) CGGP-pseudodifferential operator $(\Delta_{G,R}^{(0)})^{-1}$ such that
\[
(\Delta_{G,R}^{(0)})^{-1} \Delta_{G,R}^{(0)} = \text{Id} \text{ on } \mathcal{E}'(\mathbb{G}, E_{0}^{h}) \text{ (mod } \mathcal{O}C^{-\infty}),
\]
and
\[
\Delta_{G,R}^{(0)}(\Delta_{G,R}^{(0)})^{-1} = \text{Id} \text{ on } \mathcal{E}'(\mathbb{G}, E_{0}^{h}) \text{ (mod } \mathcal{O}C^{-\infty}).
\]

Proof. Keeping in mind [5], Theorem 5.1 and Theorem 5.11, it follows from Rockland’s condition (see Theorem 6.4), that is satisfied by [24], that there exists $(\Delta_{G}^{(0)})^{-1} \in K^{-Q}$ such that
\[
(\Delta_{G}^{(0)})^{-1} \Delta_{G}^{(0)} = \Delta_{G}^{(0)} \ast (\Delta_{G}^{(0)})^{-1} = \delta.
\]
The assertion follows taking now $(\Delta_{G,R}^{(0)})^{-1} := \mathcal{O}(\Delta_{G,R}^{(0)})^{-1}$ for $R > 0$.

Remark 4.9. If $\alpha \in \mathcal{E}'(B(e, r), E_{0}^{h})$, then, by Lemma 6.13, both
\[
\text{supp} (\Delta_{G,R}^{(0)})^{-1} \Delta_{G,R}^{(0)} \alpha \text{ and } \text{supp} (\Delta_{G,R}^{(0)} \Delta_{G,R}^{(0)})^{-1} \alpha
\]
are contained in a fixed ball $B$ depending only on $r, R$. Thus, we can multiply the identities (34) and (35) by a suitable test function $\varphi$ that is identically
one on $B$, and then we can replace the smoothing operators $S$ appearing in (34) and (35) by operators of the form $\varphi S$, that maps $\mathcal{E}'(\mathcal{G}, E^h_0)$ in $\mathcal{D}(\mathcal{G}, E^h_0)$.

Proposition 4.10. For any $R > 0$

\begin{equation}
(36) \quad (\Delta^{(0)}_{G,R})^{-1}\tilde{d}_c = \tilde{d}_c(\Delta^{(0)}_{G,R})^{-1} \text{ on } \mathcal{E}'(\mathcal{G}, E^h_0) \pmod{\mathcal{O}C^{-\infty}},
\end{equation}

and

\begin{equation}
(37) \quad (\Delta^{(0)}_{G,R})^{-1}\tilde{\alpha} = \tilde{\alpha}(\Delta^{(0)}_{G,R})^{-1} \text{ on } \mathcal{E}'(\mathcal{G}, E^h_0) \pmod{\mathcal{O}C^{-\infty}}.
\end{equation}

Proof. By duality, it is enough to prove (36). In the sequel, $S$ will always denote a smoothing operator belonging to $\mathcal{O}C^{-\infty}$ that may change from formula to formula, and, with the same convention, we shall denote by $S_0$ an operator of the form $\varphi S$, with $S \in \mathcal{O}C^{-\infty}$ and $\varphi \in \mathcal{D}(\mathcal{G})$. Keeping in mind Remark 4.9, we have

\begin{equation}
(\Delta^{(0)}_{G,R})^{-1} \tilde{d}_c = (\Delta^{(0)}_{G,R})^{-1} \Delta^{(0)}_{G,R} \tilde{d}_c (\Delta^{(0)}_{G,R})^{-1} + S_0
\end{equation}

\begin{equation}
= (\Delta^{(0)}_{G,R})^{-1} (\tilde{d}_c \tilde{d}_c + \tilde{d}_c \tilde{d}_c) + (\Delta^{(0)}_{G,R})^{-1} + S_0
\end{equation}

\begin{equation}
= (\Delta^{(0)}_{G,R})^{-1} \tilde{d}_c (\Delta^{(0)}_{G,R})^{-1} + S_0
\end{equation}

\begin{equation}
= (\Delta^{(0)}_{G,R})^{-1} \tilde{\alpha} (\Delta^{(0)}_{G,R})^{-1} + S_0
\end{equation}

Remark 4.11. We can repeat the arguments of Remark 4.9 also for (36) and (37).

Proof of Theorem 4.1. In the sequel, $S$ will always denote a smoothing operator belonging to $\mathcal{O}C^{-\infty}$ that may change from formula to formula, and, with the same convention, we shall denote by $S_0$ an operator of the form $\varphi S$, with $S \in \mathcal{O}C^{-\infty}$ and $\varphi \in \mathcal{D}(\mathcal{G})$. Moreover, without loss of generality, we may assume $\alpha^{\epsilon} \in \mathcal{D}(\Omega, E^h_0)$. Take now $R > 0$ such that $\Omega \subset B(e, R)$; by Lemma 6.13, $\Delta^{-N/2}_{G,R} \alpha^{\epsilon} \in \mathcal{D}(B(e, 2R), E^h_0)$ and therefore, by (35),

\begin{equation}
(38) \quad \Delta^{(0)}_{G,R} (\Delta^{(0)}_{G,R})^{-1} \Delta^{-N/2}_{G,R} \alpha^{\epsilon} - \Delta^{-N/2}_{G,R} \alpha^{\epsilon} = S \Delta^{-N/2}_{G,R} \alpha^{\epsilon}
\end{equation}

with $S \in \mathcal{O}C^{-\infty}$. Since supp $\Delta^{(0)}_{G,R} (\Delta^{(0)}_{G,R})^{-1} \Delta^{-N/2}_{G,R} \alpha^{\epsilon} \subset B(e, 4R)$, we can multiply the previous identity by a cut-off function $\varphi_1 \equiv 1$ on $B(e, 4R)$ without affecting the left hand side of the identity. Thus, we can write (38) as

\begin{equation}
(39) \quad \Delta^{(0)}_{G,R} (\Delta^{(0)}_{G,R})^{-1} \Delta^{-N/2}_{G,R} \alpha^{\epsilon} - \Delta^{-N/2}_{G,R} \alpha^{\epsilon} = \varphi S \Delta^{-N/2}_{G,R} \alpha^{\epsilon} = S_0 \alpha^{\epsilon},
\end{equation}

by Lemma 6.10. From (39), it follows easily that

\begin{equation}
(40) \quad \Delta^{-N/2}_{G,R} (\Delta^{(0)}_{G,R})^{-1} \Delta^{-N/2}_{G,R} \alpha^{\epsilon} = \Delta^{N/2}_{G,R} \alpha^{\epsilon} + \Delta^{-N/2}_{G,R} S_0 \alpha^{\epsilon},
\end{equation}

so that, by Lemma 6.23 and arguing as above,

\begin{equation}
(41) \quad \Delta^{-N/2}_{G,R} (\Delta^{(0)}_{G,R})^{-1} \Delta^{-N/2}_{G,R} \alpha^{\epsilon} = \alpha^{\epsilon} + S_0 \alpha^{\epsilon}.
\end{equation}
If we write explicitly $\Delta_{G,R}^0$ in (41), we get

\begin{equation}
(42) \quad \alpha^\varepsilon = \Delta_{G,R}^{N_h/2} \Delta_{G,R}^{N_h/2} \delta_c \Delta_{G,R}^{N_h+1/2} \Delta_{G,R}^{N_h+1/2} d_c \Delta_{G,R}^{N_h/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h/2} \alpha^\varepsilon
+ \Delta_{G,R}^{N_h/2} \Delta_{G,R}^{N_h/2} d_c \Delta_{G,R}^{N_h-1/2} \Delta_{G,R}^{N_h-1/2} \delta_c \Delta_{G,R}^{N_h/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h/2} \alpha^\varepsilon
+ S_0 \alpha^\varepsilon := I_1 + I_2 + S_0 \alpha^\varepsilon.
\end{equation}

By Lemma 6.23,

\begin{equation}
(43) \quad I_2 = d_c \Delta_{G,R}^{N_h-1/2} \Delta_{G,R}^{N_h-1/2} \delta_c \Delta_{G,R}^{N_h/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h/2} \alpha^\varepsilon
+ S_0 \alpha^\varepsilon
:= d_c \psi^\varepsilon + S_0 \alpha^\varepsilon.
\end{equation}

Thus (42) becomes

\begin{equation}
(44) \quad \alpha^\varepsilon = \Delta_{G,R}^{N_h/2} \Delta_{G,R}^{N_h/2} \delta_c \Delta_{G,R}^{N_h+1/2} \Delta_{G,R}^{N_h+1/2} d_c \Delta_{G,R}^{N_h/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h/2} \alpha^\varepsilon
+ S_0 \alpha^\varepsilon + d_c \psi^\varepsilon := \omega^\varepsilon + d_c \psi^\varepsilon.
\end{equation}

We want to show that $(\psi^\varepsilon)_{\varepsilon>0}$ and $(\omega^\varepsilon)_{\varepsilon>0}$ converge strongly in $L^s_{\text{loc}}(\mathbb{G}, E_0^{h-1})$ and $L^s(\mathbb{G}, E_0^h)$, respectively. By Proposition 6.22, $(\Delta_{G,R}^{N_h/2} \alpha^\varepsilon)_{\varepsilon>0}$ converges weakly in $W^{N_h-s}_{G} (\mathbb{G}, E_0^h)$. On the other hand, by Proposition 6.19, also $(\Delta_{G,R}^{N_h/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h/2} \alpha^\varepsilon)_{\varepsilon>0}$ converges weakly in $W^{N_h-s}_{G} (\mathbb{G}, E_0^h)$, and, again by Proposition 6.19, $(\Delta_{G,R}^{N_h/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h/2} \alpha^\varepsilon)_{\varepsilon>0}$ converges weakly in $W^{2N_h,s}_{G} (\mathbb{G}, E_0^h)$.

For sake of simplicity, denote now by $\beta_j^\varepsilon$, $j \in I_{0,N_h}^h$, a generic component of $\Delta_{G,R}^{N_h/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h/2} \alpha^\varepsilon$ that converges weakly in $W^{2N_h,s}_{G} (\mathbb{G}, E_0^h)$. If $i \in I_{0,N_h}^{h-1}$, then the $i$-th component of $\delta_c \beta_j^\varepsilon$ is given by $d_i L_{j,i} \beta_j^\varepsilon$. Keeping in mind that $L_{j,i}$ is a homogeneous differential operator in the horizontal vector fields of order $N_h - q$, then $(d_i L_{j,i} \beta_j^\varepsilon)_{\varepsilon>0}$ converges weakly in $W^{N_h+q,s}_{G} (\mathbb{G}, E_0^h)$, so that, eventually, the $i$-th component of $(\omega^\varepsilon)_{\varepsilon>0}$ converges weakly in $W^{N_h+q,s}_{G} (\mathbb{G}, E_0^h)$. Then the assertion follows by Rellich theorem (Proposition 3.11), since supp $\psi^\varepsilon$ is contained in a fixed neighborhood of $\Omega$, and $q < N_h$.

Let us consider now $(\omega^\varepsilon)_{\varepsilon>0}$. By Lemma 6.11, we can forget the smoothing operator $S_0$. By Proposition 4.10 and Remark 4.11, we can write

\begin{equation}
(45) \quad \Delta_{G,R}^{N_h/2} \Delta_{G,R}^{N_h/2} \delta_c \Delta_{G,R}^{N_h+1/2} \Delta_{G,R}^{N_h+1/2} d_c \Delta_{G,R}^{N_h/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h/2} \alpha^\varepsilon
= \Delta_{G,R}^{N_h/2} \Delta_{G,R}^{N_h/2} \delta_c \Delta_{G,R}^{N_h+1/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h+1/2} d_c \alpha^\varepsilon + S_0 \alpha^\varepsilon
= \Delta_{G,R}^{N_h/2} (\Delta_{G,R}^0)^{-1} \Delta_{G,R}^{N_h+1/2} \delta_c \Delta_{G,R}^{N_h+1/2} \Delta_{G,R}^{N_h+1/2} d_c \alpha^\varepsilon + S_0 \alpha^\varepsilon.
\end{equation}

By Proposition 6.22,

\[\Delta_{G,R}^{N_h+1/2} \Delta_{G,R}^{N_h+1/2} d_c \alpha^\varepsilon\] is pre-compact in $W^{N_h+1+N_h,s}_{G,\text{loc}}(\mathbb{G}, E_0^h)$.

Arguing as above, denote now by $\beta_j^\varepsilon$, $j \in I_{0,N_h}^{h+1}$, a generic component of $\beta^\varepsilon := \Delta_{G,R}^{N_h+1/2} \Delta_{G,R}^{N_h+1/2} d_c \alpha^\varepsilon$. We know that $\beta_j^\varepsilon$ is pre-compact in $W^{N_h+1+N_h,s}_{G,\text{loc}}(\mathbb{G}, E_0^{h+1})$. \[27\]
Moreover notice that $\delta c \beta_\varepsilon$ is a $h$-form, and therefore, by assumption, has pure weight $N_h$. If $i \in I_{0,N_h}^h$ ($N_h < p$), then the $i$-th component of $\delta c \beta_\varepsilon^j$ is given by $L_{j,i} \beta_\varepsilon^j$. Keeping in mind that $L_{j,i}$ is a homogeneous differential operator in the horizontal vector fields of order $j - i = p - N_h$, then $(\delta c \beta_\varepsilon^j)_i$ is pre-compact in $W^{2,N_h}G, G_0^h \right)$. Thus, $\delta c \Delta_G^R \Delta_G^R \Delta_G^R \Delta_G^R \Delta_G^R d_c \alpha^\varepsilon$ is pre-compact in $W^{2,N_h}G, G_0^h \right)$. Again, by Proposition 6.22, $\Delta_G^R \delta c \Delta_G^R \Delta_G^R \Delta_G^R \Delta_G^R d_c \alpha^\varepsilon$ is pre-compact in $W^{2,N_h}G, G_0^h \right)$. Thus, we can rely now on formula (48) to conclude that $\Delta_G^R \delta c \Delta_G^R \Delta_G^R \Delta_G^R \Delta_G^R d_c \alpha^\varepsilon$ have the same weight and hence belong to the same Sobolev space, to conclude that 

$\Delta_G^R \delta c \Delta_G^R \Delta_G^R \Delta_G^R \Delta_G^R d_c \alpha^\varepsilon$ is pre-compact in $W^{2,N_h}G, G_0^h \right)$. Then, we achieve the proof of the theorem using again Proposition 6.22.

Finally, the last statement follows by Lemma 6.13 and Theorem 6.8, (b).

\[ \square \]

**Lemma 4.12.** If $\alpha \in E(G, E_0^h)$ with $2 \leq h \leq n$ and $\beta \in E(G, E_0^{n-h-2})$, then

\[ d \, d_c \alpha \wedge (\Pi_E \beta) = 0. \]

**Proof.** By Remark 2.16, we have

\[ d \, d_c \alpha \wedge (\Pi_E \beta) = (\Pi_E \, d \, d_c \alpha) \wedge \beta = (d \, \Pi_E \, d \, d_c \alpha) \wedge \beta = (d \, d_c \alpha) \wedge \beta = 0. \]

\[ \square \]

**Theorem 4.13.** If $1 < s_i < \infty$, $0 \leq h_i \leq n$ for $i = 1, 2$, and $0 < \varepsilon < 1$, assume that $\alpha_i^\varepsilon \in L^{h_i}(G, E_0^{h_i})$ for $i = 1, 2$, where $\frac{1}{h_1} + \frac{1}{h_2} = 1$ and $h_1 + h_2 = n$. Suppose $h_1$-forms have pure weight $N_{h_1}$ (by Hodge duality, this implies that also $h_2$-forms have pure weight $N_{h_2}$). Assume that, for any open set $\Omega_0 \subset \subset G$,

\[ \alpha_i^\varepsilon \rightharpoonup \alpha_i \ \text{weakly in} \ L^{s_i}(\Omega_0, E_0^{h_i}), \]

and that

\[ \{d_c \alpha_i^\varepsilon\} \ \text{is pre-compact in} \ W^{-(N_{h_i+1}-N_{h_i})s_i}G_0^{h_i} \]

for $i = 1, 2$.

Then

\[ \int_G \varphi \, \alpha_1^\varepsilon \wedge \alpha_2^\varepsilon \rightharpoonup \int_G \varphi \, \alpha_1 \wedge \alpha_2 \]

for any $\varphi \in D(G)$.

**Proof.** By Remark 4.2, without loss of generality we can assume that both $\alpha_1^\varepsilon$ and $\alpha_2^\varepsilon$ are smooth forms. In addition, let us prove that, if $\Omega$ is an open neighborhood of $\text{supp} \, \varphi$, then

\[ d_c(\varphi \alpha_1^\varepsilon) \ \text{is pre-compact in} \ W^{-(N_{h_1+1}-N_{h_1})s_1}G_0^{h_i}. \]
An analogous argument can be repeated for \( \psi \alpha^\varepsilon_2 \), where \( \psi \in D(\Omega) \) is identically 1 on \( \text{supp } \varphi \). Thus, without loss of generality, we could restrict ourselves to prove that

\[
(50) \quad \int_G \alpha^\varepsilon_1 \wedge \alpha^\varepsilon_2 \to \int_G \alpha_1 \wedge \alpha_2
\]

when (46) and (47) hold and \( \alpha_i \in D(\Omega, E^h_{0_i}) \) for \( i = 1, 2 \).

In order to prove (49), set \( \beta^\varepsilon := \partial_c(\varphi \alpha^\varepsilon_1) \), with \( \beta^\varepsilon = \sum_i \sum_{i \in l_{0_i}^{h+1}} \partial^\varepsilon \xi^{i+1} \).

If \( \alpha^\varepsilon_1 = \sum_p \sum_{i \in l_{0_i}^{h}} (\alpha^\varepsilon_1)_i \xi^p \), then, by Theorem 2.14, when \( i \in l_{0_i}^{h+1} \), we have

\[
\beta_i = \sum_{p<q} \sum_{j \in l_{0,p}^{h}} (L^{h}_{i,j}(\varphi(\alpha^\varepsilon_1))_j) \\
= \varphi \sum_{p<q} \sum_{j \in l_{0,p}^{h}} L^{h}_{i,j}(\alpha^\varepsilon_1)_j + \sum_{p<q} \sum_{j \in l_{0,p}^{h}} \sum_{1 \leq |\gamma| \leq q-p} (P_{\gamma} \varphi)(Q_{\gamma}(\alpha^\varepsilon_1))_j \\
= \varphi(\partial_c(\alpha^\varepsilon_1))_i + \sum_{p<q} \sum_{j \in l_{0,p}^{h}} \sum_{1 \leq |\gamma| \leq q-p} (P_{\gamma} \varphi)(Q_{\gamma}(\alpha^\varepsilon_1))_j,
\]

where \( P_{\gamma} \) and \( Q_{\gamma} \) are homogeneous left invariant differential operators of order \( |\gamma| \) and \( q - p - |\gamma| \), respectively, in the horizontal derivatives. By (47), \( \varphi(\partial_c(\alpha^\varepsilon_1))_i \) is compact in \( W^-(q-p,s)_G(\Omega) \). On the other hand \( Q_{\gamma}(\alpha^\varepsilon_1)_j \) is bounded in \( W^-(q-p-|\gamma|,s)_G(\Omega) \), and therefore compact in \( W^-(q-p,s)_G(\Omega) \) by Proposition 3.11, since \( |\gamma| > 0 \). This proves (49).

We can proceed now to prove (50). By Theorem 4.1 we can write

\[
\alpha^\varepsilon_i = \partial_c \psi^\varepsilon_i + \omega^\varepsilon_i, \quad i = 1, 2,
\]

with \( \psi^\varepsilon_i \) and \( \omega^\varepsilon_i \) supported in a suitable neighborhood \( \Omega_0 \) of \( \bar{\Omega} \) and converging strongly in \( L^\infty(\Omega_0, E^h_{0_i}) \). Thus the integral of \( \alpha^\varepsilon_1 \wedge \alpha^\varepsilon_2 \) in (50) splits into the sum of 4 terms. Clearly, 3 of them are easy to deal with, since they are the integral of the wedge product of two sequences of forms, at least one of them converging strongly. Thus, we are left with the term

\[
\int_G \partial_c \psi^\varepsilon_1 \wedge \partial_c \psi^\varepsilon_2,
\]
with \( \psi^i \in D(\Omega_0, E^{h_0}_0) \) for \( i = 1, 2 \). We have
\[
\int_G d_c \psi^1 \wedge d_c \psi^2 = \int_G (d \Pi_{E_0} \psi^1) \wedge (d_c \psi^2)
\]
\[
= \int_G (d \Pi_{E_0} \psi^1) \wedge (d_c \psi^2) \quad \text{(by (23))}
\]
\[
= \int_G d \left( (\Pi_{E_0} \psi^1) \wedge (d_c \psi^2) \right) + (-1)^{h_1} \int_G (\Pi_{E_0} \psi^1) \wedge d (d_c \psi^2)
\]
\[
= (-1)^{h_1} \int_G (\Pi_{E_0} \psi^1) \wedge d (d_c \psi^2) \quad \text{(by Stokes theorem)}
\]
\[
= (-1)^{h_1} \int_G \psi^1 \wedge (\Pi_{E_0} d (d_c \psi^2)) \quad \text{(by (22))}
\]
\[
= (-1)^{h_1} \int_G \psi^1 \wedge (d \Pi_{E_0} (d_c \psi^2)) \quad \text{(by (21))}
\]
\[
= (-1)^{h_1} \int_G \psi^1 \wedge (d_c (d_c \psi^2)) \quad \text{(again by (23))}
\]
\[
= 0,
\]
since \( d_c^2 = 0 \). This achieves the proof of the theorem. \( \square \)

5. DIV–CURL THEOREM AND H–CONVERGENCE

We state some dual formulations of our main theorem for horizontal vector fields in \( G \), i.e. for sections of \( HG \). Since in this case the compensated compactness theorem takes a form akin to the original form of the theorem proved by Murat and Tartar, we can refer to it as to the div – curl theorem for Carnot groups. In this case, our compensated compactness theorem applies for any Carnot group \( G \), since, as pointed out in Example 7.4, \( E^0_0 \) consists precisely of all forms of pure weight 1. In addition, as in [12] and [2], the div – curl theorem makes possible to develop a theory of the \( H \)-convergence for second order divergence form elliptic differential operators in Carnot groups of the form
\[
\mathcal{L} u := \sum_{i,j=1}^m X_i^* (a_{ij}(x) X_j u) = f \in W^{-1,2}_G(\Omega)
\]
\[
u = 0 \quad \text{on } \partial \Omega,
\]
with application for instance to non-periodic homogenization. Here \( A(x) := (a_{i,j}(x))_{i,j=1,\ldots,m} \) is a \( m \times m \) elliptic matrix with measurable entries.

We stress again that \( \mathcal{L} \) is elliptic with respect to the structure of the group \( G \), but is degenerate elliptic as an usual differential operator in \( \mathbb{R}^n \).

If \( V \) is an horizontal vector field, i.e. if \( V \) is a section of \( HG \), as customary we set
\[
\text{div}_G V := (d_c(\ast V^2))^2,
\]
and
\[
\text{curl}_G V := (d_c V^2)^2.
\]
Moreover, if \( f \) is a function, we denote by \( \nabla_G f \) the horizontal vector field \( \nabla_G f := (X_1 f, \ldots, X_m f) \). Set now \( E_{0,h} := (E^0_0)^2 \) (with the induced scalar product). An orthonormal basis of \( E_{0,1} \) is given by \( X_1, \ldots, X_m \), and hence the horizontal vector field \( V \) can be written in the form \( V := \sum_{j=1}^m V_j X_j \)
and therefore identified with the vector-valued function \((V_1, \ldots, V_m)\). In the sequel, we write also \((V_{X_1}, \ldots, V_{X_m})\). Thus \(\nabla G = \sum_{j=1}^m X_j V_j\). The Dirichlet problem (51) takes the form

\[
\begin{align*}
L u &:= -\nabla G (A(x)) \nabla G u = f \in W^{-1,2}_G (\Omega), \\
u & = 0 \quad \text{on } \partial \Omega.
\end{align*}
\]

If we refer to the examples of Appendix B, the operator \(\text{curl}_G\) on a horizontal vector field \(V\) takes the following forms:

- **Example 7.5:** if \(V = (V_X, V_Y)\), then
  \[
  \text{curl}_G V = P_1 (V_X, V_Y) X \wedge T + P_2 (V_X, V_Y) Y \wedge T.
  \]
  Let \(D\) be another horizontal vector field. In this case, assumption (47) of Theorem 4.13 requires that all the coefficients of \(\text{curl}_G (V_X, V_Y)\) be compact in \(W^{-2, \alpha_1}_{G, \text{loc}} (\mathbb{G})\), \(i = 1, 2\)

and \(\text{div}_G D\) compact in \(W^{-1, \alpha_2}_{G, \text{loc}} (\mathbb{G})\).

- **Example 7.6:** if \(V = (V_X, V_Y, V_S)\), then
  \[
  \text{curl}_G V = P_1 (V_X, V_Y) X \wedge T + P_2 (V_X, V_Y) Y \wedge T
  + (XV_S - SV_X)X \wedge S + (YV_S - SV_Y)Y \wedge S.
  \]
  As above, (47) of Theorem 4.13 becomes

  \[
  P_i (V_X, V_Y) \quad \text{compact in } W^{-2, \alpha_1}_{G, \text{loc}} (\mathbb{G}), \quad i = 1, 2
  \]
  \[
  XV_S - SV_X, \quad YV_S - SV_Y \quad \text{compact in } W^{-1, \alpha_1}_{G, \text{loc}} (\mathbb{G}),
  \]

and \(\text{div}_G D\) compact in \(W^{-1, \alpha_2}_{G, \text{loc}} (\mathbb{G})\).

- **Example 7.7:** if \(V = (V_{X_1}, V_{X_2}, V_{Y_1}, V_{Y_2}, V_S)\), then
  \[
  \text{curl}_G V = (X_1 \alpha X_2 - X_2 \alpha X_1) X_1 \wedge X_2 + (Y_1 \alpha Y_2 - Y_2 \alpha Y_1) Y_1 \wedge Y_2
  + (X_1 \alpha Y_2 - Y_2 \alpha X_1) Y_1 \wedge Y_2 + (X_2 \alpha Y_1 - Y_1 \alpha X_2) X_2 \wedge Y_1
  + (X_1 \alpha S - S \alpha X_1) X_1 \wedge S + (X_2 \alpha S - S \alpha X_2) X_2 \wedge S
  + (Y_1 \alpha S - S \alpha Y_1) Y_1 \wedge S + (Y_2 \alpha S - S \alpha Y_2) Y_2 \wedge S
  + \frac{X_1 \alpha Y_1 - Y_1 \alpha X_1 - X_2 \alpha Y_2 + Y_2 \alpha X_2}{\sqrt{2}} \left( X_1 \wedge Y_1 - X_2 \wedge Y_2 \right).
  \]
  Here, assumption (47) requires that all the coefficients of \(\text{curl}_G V\), as well as \(\text{div}_G D\), are compact in \(W^{-1, \alpha_1}_{G, \text{loc}} (\mathbb{G})\), and \(W^{-1, \alpha_2}_{G, \text{loc}} (\mathbb{G})\), respectively.

- **Example 7.8:** if \(V = (V_{X_1}, V_{X_2}, V_{X_3}, V_{X_4}, V_{X_5}, V_{X_6})\), then
  \[
  \text{curl}_G V = (X_1 \alpha X_3 - X_3 \alpha X_1) X_1 \wedge X_3 + (X_1 (X_1 \alpha X_2 - X_2 \alpha X_1)
  - X_4 \alpha X_1) X_1 \wedge X_4
  + (X_2 (X_1 \alpha X_2 - X_2 \alpha X_1) - X_4 \alpha X_2) X_2 \wedge X_4
  + (X_2 (X_2 \alpha X_3 - X_3 \alpha X_2) - X_5 \alpha X_2) X_2 \wedge X_5
  + (X_3 (X_2 \alpha X_3 - X_3 \alpha X_2) - X_5 \alpha X_3) X_3 \wedge X_5.
  \]
As above, (47) of Theorem 4.13 becomes
\[ X_1 \alpha_{X_3} - X_3 \alpha_{X_1} \text{ compact in } W^{-1,s_1}_{G,\text{loc}}(G), \]
\[ X_1(X_1 \alpha_{X_2} - X_2 \alpha_{X_1}) - X_4 \alpha_{X_1}, \quad X_2(X_1 \alpha_{X_2} - X_2 \alpha_{X_1}) - X_1 \alpha_{X_2}, \]
\[ X_2(X_2 \alpha_{X_3} - X_3 \alpha_{X_2}) - X_5 \alpha_{X_2} \text{ compact in } W^{-2,s_1}_{G,\text{loc}}(G), \]
\[ X_3(X_2 \alpha_{X_3} - X_3 \alpha_{X_2}) - X_5 \alpha_{X_3} \text{ compact in } W^{-3,s_1}_{G,\text{loc}}(G), \]
and
\[ \text{div}_G D \text{ compact in } W^{-1,s_2}_{G,\text{loc}}(G). \]

- Example 7.9: if \( V = (V_1, V_2) \), then
  \[
  \text{curl}_G V = (X_2(X_1 V_2 - X_2 V_1) - X_3 V_2) X_2 \wedge X_3 \\
  + (X_1(X_1^2 V_2 - (X_1 X_2 + X_3) V_1) - X_4 V_1) X_1 \wedge X_4.
  \]
  As above, (47) of Theorem 4.13 becomes
  \[ X_2(X_1 V_2 - X_2 V_1) - X_3 V_2 \text{ compact in } W^{-2,s_1}_{G,\text{loc}}(G), \]
  \[ X_1(X_1^2 V_2 - (X_1 X_2 + X_3) V_1) - X_4 V_1 \text{ compact in } W^{-3,s_1}_{G,\text{loc}}(G), \]
  and
  \[ \text{div}_G D \text{ compact in } W^{-1,s_2}_{G,\text{loc}}(G). \]

- Example 7.10: if \( V = (V_1, V_2) \), then
  \[
  \text{curl}_G V = (X_1(X_1^2 V_2 - X_1 X_2 V_1 - X_3 V_1) - X_4 V_1) X_1 \wedge X_4 \\
  + (X_2(X_2 X_1 V_2 - X_2^2 V_1 - X_3 V_2 - X_5 V_2) X_2 \wedge X_5 \\
  + \frac{1}{2} (X_1(X_2 X_1 V_2 - X_2^2 V_1 - X_3 V_2) - X_5 V_1 \\
  + X_2(X_1^2 V_2 - X_1 X_2 V_1 - X_3 V_1) - X_4 V_2) (X_1 \wedge X_5 + X_2 \wedge X_4).
  \]

Here, assumption (47) requires that all the coefficients of \( \text{curl}_G V \) are compact in \( W^{-3,s_1}_{G,\text{loc}}(G) \), and that \( \text{div}_G D \) is compact in \( W^{-1,s_2}_{G,\text{loc}}(G) \).

Theorem 4.13 yields the following result that generalizes to arbitrary Carnot groups Theorem 3.3 of [12] and Theorem 5.5 of [2], extending to the setting of Carnot groups Theorem 5.3 and its Corollary 5.4 of [14].

**Theorem 5.1.** Let \( \Omega \subset \mathbb{H}^n \) be an open set, and let \( s, \sigma > 1 \) be a Hölder conjugate pair. Moreover, with the notations of (26), if \( p \in I_0^2 \) (i.e. if \( p \geq 2 \) is the weight of an intrinsic 2-form), let \( a(p) > 1 \) and \( b > 1 \) be such that
\[
a(p) > \frac{Qs}{Q + (p - 1)s} \quad \text{and} \quad b > \frac{Q\sigma}{Q + \sigma}.
\]

Let now \( E^k \in L^p_{loc}(\Omega, H \mathbb{G}) \) and \( D^k \in L^p_{loc}(\Omega, H \mathbb{G}) \) be horizontal vector fields for \( k \in \mathbb{N} \), weakly convergent to \( E \) and \( D \) in \( L^p_{loc}(\Omega, H \mathbb{G}) \) and in \( L^p_{loc}(\Omega, H \mathbb{G}) \), respectively.

If the components of \( \{\text{curl}_G E^k\} \) of weight \( p \) are bounded in \( L_{loc}^{p(p)}(\Omega, H \mathbb{G}) \) for \( p \in I_0^2 \) and \( \{\text{div}_G D^k\} \) is bounded in \( L_{loc}^{p(p)}(\Omega, H \mathbb{G}) \), then
\[
\langle E^k, D^k \rangle \to \langle E, D \rangle \quad \text{in } \mathcal{D}'(\Omega),
\]
Indeed, the components of $\{E_k\}$ are compact in $W^{-1,\sigma}_{G,\text{loc}}(\Omega)$ and the components of $\{\text{curl}_{G} E_k\}$ of weight $p$ are compact in $W^{-1,p,s}_{G,\text{loc}}(\Omega)$. Indeed, $p-1$ is precisely the component of index $p$ of $N_2 - 1 = N_2 - N_1$.

But this follows by a simple computation from Remark 3.12, since

(i) $L^b_{\text{loc}}(\Omega, H G)$ is compactly embedded in $W^{-1,\sigma}_{G,\text{loc}}(\Omega)$;
(ii) $L^{a(p)}_{\text{loc}}(\Omega, H G)$ is compactly embedded in $W^{-1,p,s}_{G,\text{loc}}(\Omega)$.

Indeed, in order to prove i), it is enough to notice that

$$b'(1 - Q/s) + Q > b'(1 - Q/s + Q(1 - 1/\sigma - 1/Q)) = 0,$$

whereas, to prove ii) we notice that

$$a(p)'(p - 1 - Q/\sigma) + Q > a(p)'(p - 1 - \frac{Q}{\sigma} + Q(1 - \frac{Q + (p - 1)s}{Qs})) = 0.$$

\[\square\]

In particular, as we pointed out above, Theorem 5.1 makes possible to extend the notion of Murat–Tartar $H$-convergence (see e.g. [19]), given in [12] and [2] for $G = \mathbb{H}^n$, to an arbitrary Carnot group $G$. In fact, the definitions given in [12] and [2] are naturally stated in general Carnot groups as follows.

**Definition 5.2.** If $0 < \alpha \leq \beta < \infty$ and $\Omega$ is an open subset of $\mathbb{G}$, we denote by $M(\alpha, \beta; \Omega)$ the set of $(m \times m)$-matrix-valued measurable functions in $\Omega$ such that

$$\langle A(x)\xi, \xi \rangle_{\mathbb{R}^m} \geq \frac{1}{\beta} |A(x)|^2_{\mathbb{R}^m} \quad \text{and} \quad \langle A(x)\xi, \xi \rangle_{\mathbb{R}^m} \geq \alpha |\xi|^2_{\mathbb{R}^m}$$

for all $\xi \in \mathbb{R}^m$ and for a.e. $x \in \Omega$.

**Definition 5.3.** We say that a sequence of matrices $A^k \in M(\alpha, \beta; \Omega)$ $H$-converges to the matrix $A^{eff} \in M(\alpha', \beta'; \Omega)$ for some $0 < \alpha' \leq \beta' < \infty$, if for every $f \in W^{-1,2}_G(\Omega)$, called $u_k$ the solutions in $\dot{W}^{1,2}_G(\Omega)$ of the problems

$$-\text{div}_G (A^k \nabla_G u_k) = f,$$

the following convergences hold:

$$u_k \to u_\infty \text{ in } \dot{W}^{1,2}_G(\Omega) - \text{ weak}$$

$$A^k \nabla_G u_k \to A^{eff} \nabla_G u_\infty \text{ in } L^2(\Omega; H G) - \text{ weak}.$$ 

Therefore $u_\infty$ is solution of the problem $-\text{div}_G (A^{eff} \nabla_G u_\infty) = f$ in $\Omega$.

Repeating verbatim the arguments of Theorem 4.4 of [12], we can show now that the sets $M(\alpha, \beta; \Omega)$ are compact in the topology of the $H$-convergence.
Theorem 5.4. If $0 < \alpha \leq \beta < \infty$ and $\Omega$ is a bounded open subset of $\mathbb{G}$, then for any sequence of matrices $A^n \in M(\alpha, \beta; \Omega)$ there exists a subsequence $A^k$ and a matrix $A^\infty \in M(\alpha, \beta; \Omega)$ such that $A^k \overset{H}{\rightharpoonup} A^\infty$.

6. Appendix A: Pseudodifferential Operators

To keep the paper as much self-contained as possible, we open this appendix by reminding some basic definitions and results taken from [5] on pseudodifferential operators on homogeneous groups.

We set
\[ S_0 := \{ u \in \mathcal{S} : \int_{\mathbb{G}} x^\alpha u(x) \, dx = 0 \} \]
for all monomials $x^\alpha$.

If $\alpha \in \mathbb{R}$ and $\alpha \notin \mathbb{Z}^+ := \mathbb{N} \cup \{0\}$, then we denote by $K^\alpha$ the set of the distributions in $\mathbb{G}$ that are smooth away from the origin and homogeneous of degree $\alpha$, whereas, if $\alpha \in \mathbb{Z}^+$, we say that $K \in \mathcal{D}'(\mathbb{G})$ belongs to $K^\alpha$ if it has the form
\[ K = \tilde{K} + p(x) \ln |x|, \]
where $\tilde{K}$ is smooth away from the origin and homogeneous of degree $\alpha$, and $p$ is a homogeneous polynomial of degree $\alpha$.

Kernels of type $\alpha$ according to Folland [9] belong to $K^{\alpha-Q}$. In particular, if $0 < \alpha < Q$, and $h(t,x)$ is the heat kernel associated with the sub-Laplacian $\Delta_G$, then (\cite{9}, Proposition 3.17) the kernel $R_\alpha \in L^1_{\text{loc}}(\mathbb{G})$ defined by
\[ R_\alpha(x) := \frac{1}{\Gamma(\alpha/2)} \int_0^\infty t^{(\alpha/2)-1} h(x,t) \, dt \]
belongs to $K^{\alpha-Q}$.

If $K \in K^\alpha$, we denote by $\mathcal{O}_0(K)$ the operator defined on $S_0$ by $\mathcal{O}_0(K)u := u * K$.

Proposition 6.1 ([5], Proposition 2.2). $\mathcal{O}_0(K) : S_0 \to S_0$.

Theorem 6.2 (see [15], [16]). If $K \in K^{-Q}$, then $\mathcal{O}_0(K) : L^2(\mathbb{G}) \to L^2(\mathbb{G})$.

Remark 6.3. We stress that, with the notations of Appendix 6.6, we have also
\[ S_0(\mathbb{G}) \subset \text{Dom} (\Delta_G^{-\alpha/2}) \quad \text{with} \quad \alpha > 0. \]
Indeed, take $M \in \mathbb{N}$, $M > \alpha/2$. If $u \in S_0(\mathbb{G})$, we can write $u = \Delta_G^M v$, where
\[ v := (\mathcal{O}_0(R_2) \circ \mathcal{O}_0(R_2) \circ \cdots \circ \mathcal{O}_0(R_2))u \in S_0(\mathbb{G}) \]
($M$ times). Since $v \in \text{Dom} (\Delta_G^M) \cap \text{Dom} (\Delta_G^{-\alpha/2})$ (by Proposition 3.4), then $u = \Delta_G^M v \in \text{Dom} (\Delta_G^{-\alpha/2})$, and $\Delta_G^{-\alpha/2} v = \Delta_G^{-\alpha/2} \Delta_G^M v$, by [9], Proposition 3.15, (iii).

Theorem 6.4 (see [13] and [5], Theorem 5.11). If $K \in K^{-Q}$, and let the following Rockland condition hold: for every nontrivial irreducible unitary representation $\pi$ of $\mathbb{G}$, the operator $\pi_K$ is injective on $\mathcal{C}^\infty(\pi)$, the space of smooth vectors of the representation $\pi$. Then the operator $\mathcal{O}_0(K) : L^2(\mathbb{G}) \to L^2(\mathbb{G})$ is left invertible.

Obviously, if $\mathcal{O}_0(K)$ is formally self-adjoint, i.e. if $K = ^\dagger K$, then $\mathcal{O}_0(K)$ is also right invertible.
Proposition 6.5 ([5], Proposition 2.3). If $K_i \in K^\alpha_i$, $i = 1, 2$, then there exists at least one $K \in K^{\alpha_1 + \alpha_2 + Q}$ such that
\[ O_0(K_2) \circ O_0(K_1) = O_0(K). \]
It is possible to provide a standard procedure yielding such a $K$ (see [5], p.42). Following [5], we write $K = K_2 \ast K_1$.

We can give now a (simplified) definition of pseudodifferential operator on $G$, following [5], Definition 2.4.

Definition 6.6. If $\alpha \in \mathbb{R}$, we say that $K$ is a pseudodifferential operator of order $\alpha$ on $G$ with core $K$ if
\begin{enumerate}
\item $K \in D'(G \times G)$.
\item Let $\beta := -Q - \alpha$. There exist $K^m = K^m_x \in K^{\beta + m}$ depending smoothly on $x \in G$ such that for each $N \in \mathbb{N}$ there exists $M \in \mathbb{Z}^+$ such that, if we set
\[ K_x - \sum_{m=0}^{M} K^m_x := E_M(x, \cdot), \]
then $E_M \in C^N(G \times G)$.
\item For some finite $R \geq 0$, supp $K_x \subset B(e, R)$ for all $x \in G$.
\item If $u \in D(G)$ and $x \in G$, then
\[ Ku(x) = (u * K_x)(x). \]
\end{enumerate}

We write $K \sim \sum_m K^m$, $K = O(K)$, and $r(K) = r(K) = \inf \{ R > 0 \text{ such that 3 holds} \}$.

We let
\[ OC^\alpha(G) := \{ \text{pseudodifferential operators of order } \alpha \text{ on } G \}. \]

Clearly, if $K \in OC^\alpha(G)$, then $K : D(G) \to E(G)$. Moreover, $K$ can be extended to an operator $K : E'(G) \to D'(G)$.

Lemma 6.7. If supp $u \subset B(e, \rho)$, then supp $Ku \subset B(e, \rho + r(K))$.

If $\gamma = (\gamma_1, \ldots, \gamma_n) \in (\mathbb{Z}^+)^n$, for any $f \in D'(G)$ we set
\[ M_\gamma f = x^\gamma f, \]
and, if $X = (X_1, \ldots, X_n)$ is our fixed basis of $\mathfrak{g}$, we denote by $\sigma_\gamma(X)$ the coefficient of $x^\gamma$ in the expansion of $(\gamma! / |\gamma|!)(x \cdot X)^{d(\gamma)}$.

Theorem 6.8 ([5], Theorem 2.5). We have:
\begin{enumerate}
\item If $K := O(K) \in OC^\alpha(G)$, then there exists a core $K^*$ such that $O(K^*) \in OC^\alpha(G)$ and
\[ \langle v, Ku \rangle_{L^2(G)} = \langle O(K^*)v, u \rangle_{L^2(G)} \]
for all $u, v \in D(G)$.
\item If $K \in OC^\alpha(G)$, $V \subset G$ is an open set, and $u \in E'(G)$ is smooth on $V$, then $Ku$ is smooth on $V$.
\end{enumerate}
(c) If \( K_i \in \mathcal{OC}^\alpha_i(G) \), \( K_i \sim \sum m K_i^m \), \( i = 1, 2 \), then \( K := K_2 \circ K_1 \) (that is well defined by Lemma 6.7) belongs to \( \mathcal{OC}^\alpha_1 + \alpha_2(G) \). Moreover \( K \sim \sum m K^m \), where

\[
K^m_x = \sum_{d(\gamma) + j + \ell = m} \frac{1}{\Gamma_j} [(-M)^\gamma(K^j_\ell)_x] \ast [\sigma_\gamma(X)(K^j_\ell)_x],
\]

where \( \sigma_\gamma(X) \) acts in the \( x \)-variable.

**Theorem 6.9** (see [5], p.63 (3)). If \( K \in \mathcal{OC}^\alpha(G) \), then \( O(K) : L^p_0(G) \to L^p_0(G) \) is continuous. In particular, by Lemma 6.7, \( O(K) : L^p(G) \cap \mathcal{E}'(B(e, \rho)) \to L^p(G) \) continuously.

We say that a convolution operator \( u \to u \ast E(x, \cdot) \) from \( \mathcal{D}' \) to \( \mathcal{D}' \) belongs to \( \mathcal{OC}^{-\infty}(G) \) if \( E \) is smooth on \( G \times G \). We notice that, properly speaking, \( \mathcal{OC}^{-\infty}(G) \) is not contained in \( \mathcal{OC}^\alpha(G) \) for \( \alpha \in \mathbb{R} \), since \( E(x, \cdot) \) is not assumed to be compactly supported.

If \( T, S \in \mathcal{OC}(G) \), we say that \( S = T \mod \mathcal{OC}^{-\infty} \) if \( S - T \in \mathcal{OC}^{-\infty}(G) \).

A straightforward computation proves the following result

**Lemma 6.10.** If \( S \in \mathcal{OC}^{-\infty}(G) \), \( \varphi \in \mathcal{D}(G) \), and \( O(K) \in \mathcal{OC}^m(G) \) for \( m \in \mathbb{R} \), then both \( (\varphi S) \circ O(K) \) and \( O(K) \circ (\varphi S) \) belong to \( \mathcal{OC}^{-\infty}(G) \).

**Lemma 6.11.** If \( \Omega \subset G \) is a bounded open set, \( m, m' \in \mathbb{R} \), \( 1 < s < \infty \), and \( T \in \mathcal{OC}^{-\infty}(G) \), then, if \( \varphi \in \mathcal{D}(G) \), the map

\[
\varphi T : W^{m, s}_G(\mathbb{G}) \cap \mathcal{E}'(\Omega) \to W^{m', s}_G(\mathbb{G})
\]

is compact.

**Proof.** Let us prove first that the map is compact. By proposition 3.11, without loss of generality we can assume \( m < 0 < m' \), and \( |m|, m' \in \mathbb{N} \cup \{0\} \). Thus, let \( u \in W^{m, s}_G(\mathbb{G}) \cap \mathcal{E}'(\Omega) \) be given; we have to estimate

\[
\sup_{\|g\|_{L^{s'}(G)} \leq 1} \langle X^I(\varphi(u \ast T))|g\rangle
\]

for \( g \in \mathcal{D}(G) \), with \( d(I) \leq m' \), and therefore to estimate

\[
\langle (X^L \varphi)(u \ast X^J T)|g\rangle,
\]

with \( d(J) + d(L) \leq m' \), \( g \in \mathcal{D}(G) \), \( \|g\|_{L^{s'}(G)} \leq 1 \). Because of the compactness of supp \( u \), there exists \( \varphi \in \mathcal{D}(G), \varphi = \varphi(\Omega, \varphi) \) such that \( u \ast X^J T = u \ast X^J (\varphi T) \) on supp \( \varphi \). Thus, we can write

\[
\langle (X^L \varphi)(u \ast X^J T)|g\rangle = \langle u(X^L \varphi) g \ast X^J (\varphi T) \rangle
\]

\[
\leq \|u\|_{W^{m, s}_G} \sum_{d(M) \leq |m|} \| (X^L \varphi) g \ast X^{M+X^J (\varphi T)} \|_{L^{s'}(G)}
\]

\[
\leq c \|u\|_{W^{m, s}_G} \| (X^L \varphi) g \|_{L^{s'}(G)} \leq c_\varphi \|u\|_{W^{m, s}_G} \|g\|_{L^{s'}(G)},
\]

by [9], Proposition 1.10 since \( X^{M+X^J (\varphi T)} L^{1}(G) \), and then the assertion follows.

Finally, the compactness follows by the arbitrariness of the choice of \( m' \) and by Lemma 3.6. \( \square \)
From now on, let $\psi \in D(G)$ be a fixed nonnegative function such that
\[ \text{supp } \psi \subset B(e, 1) \quad \text{and} \quad \psi \equiv 1 \text{ on } B(e, \frac{1}{2}). \]
We set
\[ \psi_R := \psi \circ \delta_{1/R}. \]
If $K \in K^m$, then $K_R := \psi_R K$ is a core satisfying 1), 2), 3) of Definition 6.6. In addition, $K_R \sim K$, since we can write $K_R = K + (\psi_R - 1)K$, with $(\psi_R - 1)K \in \mathcal{E}(G)$. Thus $\mathcal{O}(K_R) \in \mathcal{OC}^{-m-Q}(G)$.

Thus, if $K$ is a Folland kernel of type $\alpha \in \mathbb{R}$, then $K_R$ is a core of a pseudodifferential operator $\mathcal{O}(K_R) \in \mathcal{OC}^{-\alpha}(G)$. In particular, if $0 < \alpha < Q$, then $\mathcal{O}((R\alpha)_R)$ belongs to $\mathcal{OC}^{-\alpha}(G)$ (see [9], Proposition 3.17).

**Lemma 6.12.** If $K \in K^m$, and $X^I$ is a left invariant homogeneous differential operator, then
\[ X^I \mathcal{O}(K_R) \in \mathcal{OC}^{-m+d(I)-Q}(G). \]
Moreover, the core $K_{R,I}$ of $X^I \mathcal{O}(K_R)$ satisfies
\[ K_{R,I} \sim X^I K, \]
and
\[ X^I \mathcal{O}(K_R) = \mathcal{O}((X^I K)_R) \mod \mathcal{OC}^{-\infty}. \]

**Proof.** It is enough to notice that, if $u \in \mathcal{E}'(G)$, then $X^I(\mathcal{O}(K_R)u) = X^I(u * K_R) = u * (X^I K_R) = u * (X^I K)_R + \sum_{0 < |J| \leq |I|} c_{IJ} u * (X^J \psi)_K$, and that $(X^I \psi)_K \in \mathcal{D}(G)$ when $|J| > 0$. \hfill \( \square \)

**Lemma 6.13.** If $u \in \mathcal{E}'(G)$ and $\text{supp } u \subset B(0, \rho)$ then $\text{supp } \mathcal{O}(K_R)u \subset B(0, R + \rho)$. Moreover, if $\rho = R$, then
\[ \mathcal{O}(K_{4R})u \equiv u * K \quad \text{on } B(0, R). \]

**Proof.** The first statement follows from Lemma 6.7. The second assertion is a straightforward computation. \hfill \( \square \)

**Proposition 6.14.** Let $K_i \in K^I$ be given cores for $i = 1, 2$, and let $R > 0$ be fixed. Then
\[ \mathcal{O}((K_2 \ast K_1)_R) = \mathcal{O}((K_1)_R) \circ \mathcal{O}((K_2)_R) \mod \mathcal{OC}^{-\infty}. \]
In particular, $\mathcal{O}((K_1)_R) \circ \mathcal{O}((K_2)_R) = \mathcal{O}(K)$ for a suitable core $K$ with $K \sim K_2 \ast K_1$.

**Proof.** It is enough to notice that, by Theorem 6.8, $\mathcal{O}((K_1)_R) \circ \mathcal{O}((K_2)_R) = \mathcal{O}(K)$, with $K \sim K_2 \ast K_1$, and that also $(K_2 \ast K_1)_R \sim K_2 \ast K_1$. \hfill \( \square \)

**Remark 6.15.** As in Remark 5 at p. 63 of [5], the previous calculus can be formulated for matrix-valued operators and hence, once left invariant bases $\{ \xi^0_{ij} \}$ of $E^0_{ij}$ are chosen, we obtain pseudodifferential operators acting on $h$-forms and $h$-currents, together with the related calculus.

In particular, let $K := (K_{ij})_{i=1,\ldots,N}^{j=1,\ldots,M}$ a $M \times N$ matrix whose entries $K_{ij}$ belong to $K^{m_{ij}}$. Then $K$ acts between $\mathcal{S}_0(G)^N$ and $\mathcal{S}_0(G)^M$ as follows: if $T = (T_1, \ldots, T_M)$, then
\[ \mathcal{O}_0(K)T := T * K := (\sum_j T_j \ast K_{1j}, \ldots, \sum_j T_j \ast K_{Mj}). \]
When $K_{ij} \in \mathbb{K}^m$ for all $i, j$, we write shortly that $K \in \mathbb{K}^m$.

If $K := (K_{ij})_{i=1,\ldots,N}^{j=1,\ldots,M}$ and $K' := (K'_{ij})_{i=1,\ldots,M'}^{j=1,\ldots,M'}$, we write

$$K'\ast K := \left( \sum_\ell K'_{ij} \ast K_{ij} \right).$$

Notice that

$$O_0(K') \circ O_0(K) = O_0(K' \ast K).$$

In addition, if $\bar{K} = (\bar{K}_{ij})$ is a matrix-valued pseudodifferential operator of the CGGP-calculus, and $K = (K_{ij})$ is a matrix-valued core as above with $\bar{K}_{ij} \sim K_{ij}$ for all $i, j$, we write $\bar{K} \sim K$, and $\bar{K} - K$ is a matrix-valued smoothing operator. As above, if all the $K_{ij}$'s are pseudodifferential operators of the same order $\alpha$, we refer to $\alpha$ as to the order of the matrix-valued pseudodifferential operator $K$.

Finally, we prove that the fractional powers of $\Delta_G$, when acting on suitable function spaces, can be written as suitable convolution operators. This is more or less known (see for instance [5], Section 6), though not explicitly stated in the form we need. Because of that, we prefer to provide full proofs.

**Theorem 6.16.** If $m \in \mathbb{R}$ and $1 < s < \infty$, then $S_0(G) \subset \text{Dom} \left( \Delta_G^{m/2} \right)$, and there exists $P_m \in \mathbb{K}^{-m-Q}$ such that

$$\Delta_G^{m/2} u = u \ast P_m \quad \text{for all} \quad u \in S_0(G).$$

Moreover, if $R > 0$ then

$$O((P_m))_R \subset \mathcal{OC}^m(G).$$

Coherently, in the sequel we shall write

$$\Delta_G^{m/2}_{G,R} := O((P_m))_R.$$  

**Proof.** Suppose first $m > 0$. By Proposition 3.4,

$$S_0(G) \subset S(G) \subset \text{Dom} \left( \Delta_G^{m/2} \right).$$

Choose $N \in \mathbb{Z}^+$ such that $m < 2N < m + Q$ (this is possible since $Q > 2$). Since $u \in \text{Dom}\Delta_G^N \cap \text{Dom}\Delta_G^{m/2}$, then, by [9], Theorem 3.15, $\Delta_G^N u \in \text{Dom}\Delta_G^{m/2-N}$ and $\Delta_G^{m/2} u = \Delta_G^{m/2-N} \Delta_G^N u$. On the other hand, $-Q < m - 2N < 0$, so that, by [9], Propositions 3.15 and 3.18,

$$\Delta_G^{m/2-N} \Delta_G^N u = \Delta_G^N u \ast R_{2N-m} = u \ast \nu(\Delta_G^N)^\nu R_{2N-m},$$

since the integral in $\Delta_G^N u \ast R_{2N-m}$ converges absolutely. Thus the assertion for $m > 0$ follows by putting $P_m := \nu(\Delta_G^N)^\nu R_{2N-m} \in \mathbb{K}^{-m-Q}$.

Let now $m := -\alpha < 0$. Choose first $N \in \mathbb{N}$ such that $2N < \alpha < Q + 2N$, that is always possible since $Q \geq 3$. This choice yields $0 < \alpha - 2N < Q$. If $u \in S_0(G)$, set

$$g := (\cdots((u \ast R_2) \ast R_2) \ast \cdots) \ast R_2$$

where we perform $N$ successive convolutions with the kernel $R_2$. By [5], Proposition 2.3,

$$g = (O_0(R_2) \circ O_0(R_2) \circ \cdots \circ O_0(R_2)) u = O_0(R_{2N}) u$$
for a suitable $R_{2,N} \in K^{2N-Q}$. Clearly, by Proposition 6.1, $g \in \mathcal{S}_0(G)$, and, in addition, $\Delta_G^N g = u$. By Remark 6.3, $g \in \text{Dom}(\Delta_G^{N-a/2})$. Since $g \in \text{Dom}(\Delta_G^N)$, by [9], Proposition 3.15 (iii), then $u = \Delta_G^N g \in \text{Dom}(\Delta_G^{N-a/2}) = \text{Dom}(\Delta_G^{m/2})$, and

$$\Delta_G^{N-a/2} g = \Delta_G^{-a/2} \Delta_G^N g = \Delta_G^{-a/2} u.$$ 

Thus, by [9], Proposition 3.18, and [5], Proposition 2.3,

$$\Delta_G^{-\alpha/2} u = O_0(R_{\alpha-2N}) g = O_0(R_{\alpha-2N})(O_0(R_{2,N}) u) := O_0(P_m) u = u * P_m,$$

where $P_m := R_{\alpha-2N}^* R_{2,N} \in K^{-m-Q}$, since $\alpha - 2N - Q + 2N - Q + Q = -m - Q$. \hfill \Box

Remark 6.17. The same argument shows that, if $m \geq 0$, then $\mathcal{D}(G) \subset \text{Dom}(\Delta_G^{m/2})$, and

$$\Delta_G^{m/2} u = u * P_m \quad \text{for all } u \in \mathcal{D}(G).$$

Lemma 6.18. We have

$$\Delta_{G,R}^{m/2} \circ \Delta_{G,R}^{-m/2} = \text{Id} \mod \mathcal{O}C^{-\infty},$$

and

$$\Delta_{G,R}^{-m/2} \circ \Delta_{G,R}^{m/2} = \text{Id} \mod \mathcal{O}C^{-\infty}.$$ 

Proof. By Theorem 6.8 (c), if $m$ is a real number, $\Delta_{G,R}^{m/2} \circ \Delta_{G,R}^{-m/2}$ has a core $K \sim P_m \# P_{-m} \in K^{-Q}$. If $u \in \mathcal{S}_0(G)$, then

$$O_0(P_m \# P_{-m}) U = O_0(P_m) \circ O_0(P_{-m}) U = \Delta_G^{m/2} \circ \Delta_G^{-m/2} U = U,$$

by Theorem 6.16 and [9], Theorem 3.15 (iii). By [15], [16], the map $u \to u * (P_m \# P_{-m})$ is continuous in $L^2(G)$, and hence, by density, $u * (P_m \# P_{-m}) = u = u * \delta$ for all $u \in \mathcal{D}(G)$. Thus the assertion is proved. \hfill \Box

Proposition 6.19. If $\Omega \subset G$ is a bounded open set, $m, \alpha, \epsilon, 1 < s < \infty$, and $T \in \mathcal{O}C^0(\Omega)$, then

$$T : W_{G}^{m+\alpha,s} (G) \cap \mathcal{E}'(\Omega) \to W_{G}^{m,s} (G)$$

continuously.

Proof. Suppose first $m, m + \alpha \geq 0$. Let $u \in W_{G}^{m+\alpha,s}(G) \cap \mathcal{E}'(\Omega)$ be given. Without loss of generality, we can assume $u \in \mathcal{D}(\Omega_1)$, where $\Omega_1$ is a given bounded open neighborhood of $\Omega$, since $\mathcal{D}(\Omega_1)$ is dense in $W_{G}^{m+\alpha,s}(G) \cap \mathcal{E}'(\Omega)$. Indeed, by Proposition 3.4, if $\varepsilon > 0$, we can find $u_\varepsilon \in \mathcal{D}(\Omega)$ such that $\|u - u_\varepsilon\|_{W_{G}^{m+\alpha,s}(G)} < \varepsilon$. Let now $\psi \in \mathcal{D}(\Omega_1)$ be such that $\psi \equiv 1$ on $\Omega$. Then, by [9], Corollary 4.15,

$$\|u - \psi u_\varepsilon\|_{W_{G}^{m+\alpha,s}(G)} = \|\psi u - \psi u_\varepsilon\|_{W_{G}^{m+\alpha,s}(G)} \leq C_\psi \|u - u_\varepsilon\|_{W_{G}^{m+\alpha,s}(G)} < C_\psi \varepsilon.$$ 

By definition, there exists a bounded open set $\Omega_T$ (depending only on $\Omega_1$ and $T$) such that $T u \in \mathcal{D}(\Omega_T)$. If $R > 0$ is fixed (sufficiently large), by Proposition 3.9, we have

$$\|T u\|_{W_{G}^{m,s}(G)} \approx \|\Delta_{G,R}^{m/2} T u\|_{L^s(G)},$$
On the other hand, by Lemma 6.18,
\[ \Delta_{G,R}^{m/2} T u = \Delta_{G,R}^{m/2} T \Delta_{G,R}^{-(m+\alpha)/2} \Delta_{G,R}^{(m+\alpha)/2} u + \varphi_0 S u, \]
with \( S \in OC^{-\infty} \) and \( \varphi_0 \in D(G) \) with \( \varphi_0 \equiv 1 \) on \( \Omega_1 \cdot B(e,2R) \), since \( \Delta_{G,R}^{-(m+\alpha)/2} \Delta_{G,R}^{(m+\alpha)/2} u \) is supported in \( \Omega_1 \cdot B(e,2R) \). Then the assertion follows by Proposition 6.19, since
\[ \Delta_{G,R}^{m/2} T \Delta_{G,R}^{-(m+\alpha)/2} \in OC^0(G), \]
by Theorem 6.8, and by Lemma 6.11.

Suppose now \( m, m + \alpha \leq 0 \). As above, if \( u \in W_{m,\alpha}(G) \cap E'(\Omega) \) then \( \text{supp } T u \) is contained in fixed open neighborhood \( \Omega_T \) of \( \Omega \). Let \( \psi_0 \in D(G) \) such that \( \psi_0 \equiv 1 \) on \( \Omega_T \). If \( \varphi \in D(G) \), by Theorem 6.8 we have
\[ \langle T u | \varphi \rangle = \langle T u | \psi_0 \varphi \rangle = \langle u | T^*(\psi_0 \varphi) \rangle \]
\[ \leq \|u\|_{W^{m,\alpha,s}(G)} \|T^*(\psi_0 \varphi)\|_{W^{-m,\alpha,s}(G)} \]
\[ \leq C \|u\|_{W^{m,\alpha,s}(G)} \|\psi_0 \varphi\|_{W^{-m,\alpha,s}(G)} \]
\[ \leq C \|u\|_{W^{m,\alpha,s}(G)} \|\varphi\|_{W^{-m,\alpha,s}(G)}, \]
by [9], Corollary 4.15. Taking the supremum with respect to \( \varphi \), the assertion follows in this case.

Suppose now \( m \leq 0 \leq m + \alpha \). As above, we can write
\[ T = \Delta_{G,R}^{-m/2} \Delta_{G,R}^{m/2} T + \varphi_0 S \]
with \( \varphi_0 \in D(G) \) and \( S \in OC^{-\infty} \).

Then the assertion follows since \( \Delta_{G,R}^{-m/2} T \in OC^{m+\alpha}(G) \), \( \Delta_{G,R}^{m/2} T \in OC^{-m}(G) \), and hence there exist a bounded open neighborhood \( \Omega_1 \) of \( \Omega \) such that
\[ \Delta_{G,R}^{m/2} T : W^{m,\alpha,s}(G) \cap E'(\Omega) \to L^s(G) \cap E'(\Omega_1) \]
and
\[ \Delta_{G,R}^{-m/2} \cap E'(\Omega_1) : L^s(G) \to W^{m,\alpha,s}(G) \]
continuously, by what we proved above.

Finally, if \( m + \alpha \leq 0 \leq m \), then the assertion follows in a similar way.

\[ \square \]

**Definition 6.20.** Let \( T \in E'(G,E^h_0) \) be a compactly supported \( h \)-current on \( G \) of the form
\[ T = \sum_p \sum_{j \in I^h_{0,p}} \tilde{T}_j \text{L}(\ast \xi_j^h) \]
with \( T_j \in E'(G) \) for \( j = 1, \ldots, \dim E^h_0 \).

Let \( m \) be a \( h \)-vector weight, and let \( R > 0 \) be fixed. We set (with the notation of (55))
\[ \Delta_{G,R}^{m/2} T := \sum_p \sum_{j \in I^h_{0,p}} (\Delta_{G,R}^{m_p/2} \tilde{T}_j) \text{L}(\ast \xi_j^h). \]

In particular, if \( T \) can be identified with a compactly supported \( h \)-form \( \alpha = \sum_p \sum_{j \in I^h_{0,p}} \alpha_j \xi_j^h \), then our previous definition becomes
\[ \Delta_{G,R}^{m/2} \alpha = \sum_p \sum_{j \in I^h_{0,p}} (\alpha_j \ast (P_{m_p}) R) \xi_j^h. \]
Remark 6.21. As in Definition 6.20, if \( \underline{m} \) is a \( h \)-vector weight, we define the operator
\[
O_0(P_{\underline{m}}) : \mathcal{S}_0(G, E_{0}^h) \to \mathcal{S}_0(G, E_{0}^h)
\]
as follows: if \( \alpha = \sum_p \sum_{j \in I_{0,p}} {\alpha_j}^{h} \) with \( \alpha_j \in \mathcal{S}_0(G) \), then
\[
O_0(P_{\underline{m}})\alpha := \sum_p \sum_{j \in I_{0,p}} (\alpha_j \ast P_{m_p})^{h}.\]
In other words, \( P_{\underline{m}} \) can be identified with the matrix \(( (P_{m})_{ij} ) \), where \( (P_{m})_{ij} = 0 \) if \( i \neq j \) and \( (P_{m})_{jj} = m_p \) if \( j \in I_{0,p}^h \).

We can write
\[
\Delta_{G,R}^{m/2} \sim P_{\underline{m}}.
\]
The following result is a straightforward consequence of Proposition 6.19, thanks to “diagonal form” of the operator \( \Delta_{G,R}^{m/2} \).

Proposition 6.22. Let \( \Omega \subset \mathbb{G} \) be a bounded open set. If \( m \) and \( \alpha \) are \( h \)-vector weights, and \( 1 < s < \infty \), then for any \( R > 0 \)
\[
\Delta_{G,R}^{\alpha/2} : W^{m+\alpha, s}(\mathbb{G}, E_{0}^h) \cap \mathcal{E}'(\Omega, E_{0}^h) \to W^{m,s}(\mathbb{G}, E_{0}^h)
\]
continuously.

Again thanks to “diagonal form” of the operator \( \Delta_{G,R}^{m/2} \), the following result is a straightforward consequence of Lemma 6.18.

Lemma 6.23. If \( \underline{m} \) is a \( h \)-vector weight, then for any \( R > 0 \)
\[
\Delta_{G,R}^{m/2} \circ \Delta_{G,R}^{-m/2} = \text{Id} \mod \mathcal{O}C^{-\infty},
\]
and
\[
\Delta_{G,R}^{-m/2} \circ \Delta_{G,R}^{m/2} = \text{Id} \mod \mathcal{O}C^{-\infty}.
\]

7. Appendix B: differential forms in Carnot groups

For sake of completeness, we present here an explicit proof of point ii) of Theorem 2.14, concerning the structure of the differential \( d_c \). Moreover, we provide a list of explicit examples of the complex \(( E_0, d_c )\) for some significant groups.

Proposition 7.1. The map \( d_c : E_{0}^h \to E_{0}^{h+1} \) can be written in the form
\[
\alpha = \sum_p \sum_{j \in I_{0,p}^h} \alpha_j^{h} \rightarrow \sum_{q = \max\{p+1, M_{h+1}^{\min}\}}^{M_{h+1}^{\max}} \sum_{i \in I_{0,q}^{h+1}} \sum_{p} \sum_{j \in I_{0,p}^h} (P_{p,q,j,i}^h \alpha_j)^{h+1}, \tag{56}
\]
where the \( P_{p,q,j,i}^h \)'s are homogeneous polynomials of degree \( q - p \) in the horizontal derivatives.

Since \( d_c = \Pi_E d \Pi_E \), the proof requires two preliminary results.
Lemma 7.2. The map $\Pi_E : E_0^{h,p} \to \Omega^h$ has the form

$$\alpha = \sum_{j \in I_p^h} \alpha_j \theta_j^{p,h} \longrightarrow \Pi_E \alpha = \sum_{j \in I_p^h} \sum_{k=0}^{N_{\max}-p} \sum_{i \in I_{p+k}^h} (Q_{p,p+k,j,i}^h \alpha_j) \theta_i^h$$

(57)

where $Q_{p,p+k,j,i}^h : \mathcal{E}(\mathbb{G}) \to \mathcal{E}(\mathbb{G})$ is an homogeneous differential operator of degree $k$ in the horizontal derivatives for all $j$, $i$ and $k$.

Proof. By linearity, we can assume $\alpha = \alpha_j \theta_j^{p,h}$ for a fixed $j$. The proof relies on Proposition 2.17 and Remark 2.18. Let us argue by induction on $k$, keeping in mind that there exist real coefficients $Q_{p,p+k,j,i}^h \alpha_j$ for $i$, $k$ with $p \leq p + k \leq N_{\max}$ and $i \in I_{p+k}^h$ such that

$$\Pi_E \alpha = \sum_{k=0}^{N_{\max}-p} (\Pi_E \alpha)_{p+k} =: \sum_{k=0}^{N_{\max}-p} \sum_{i \in I_{p+k}^h} (Q_{p,p+k,j,i}^h \alpha_j) \theta_i^h.$$

By the first line in (24), obviously $Q_{p,p+1,j,i}^h$ is an homogeneous differential operator of degree 0 in the horizontal derivatives. Suppose now $\alpha_i \to (Q_{p,p+1,j,i}^h \alpha_j)$ is an homogeneous differential operator of degree $\lambda$ in the horizontal derivatives for $\lambda \leq k$ and for all $i \in I_\lambda^h$, and let us consider now the case $\lambda = k + 1$. We have

$$(\Pi_E \alpha)_{p+k+1} = -d_{0}^{-1} \left( \sum_{\ell \leq k+1} d_{\ell} \sum_{i \in I_{p+k+1-\ell}^h} (Q_{p,p+k+1-\ell,j,i}^h \alpha_j) \theta_i^h \right)$$

$$= -d_{0}^{-1} \left( \sum_{\ell \leq k+1} \sum_{w(\theta_s)=\ell} \sum_{i \in I_{p+k+1-\ell}^h} (W_s Q_{p,p+k+1-\ell,j,i}^h \theta_s) \wedge \theta_i^h \right).$$

Now, for all $s$, $i$, $W_s(\theta_s \wedge \theta_i^h) = \ell + p + k + 1 - \ell = p + k + 1$, and the order of $W_s Q_{p,p+k+1-\ell,j,i}^h$ equals $\ell + k + 1 - \ell = k + 1$. This achieves the proof of the lemma. \square

Lemma 7.3. The map $d \Pi_E : E_0^{h,p} \to \Omega^{h+1}$ has the form

$$\alpha = \sum_{j \in I_p^h} \alpha_j \theta_j^{p,h} \longrightarrow d \Pi_E \alpha = \sum_{j \in I_p^h} \sum_{k=0}^{N_{\max}-p} \sum_{j \in I_{p+k}^h} (\breve{Q}_{p,p+k,j,i}^h \alpha_j) \theta_i^{h+1}$$

(58)

where $\breve{Q}_{p,p+k,j,i}^h : \mathcal{E}(\mathbb{G}) \to \mathcal{E}(\mathbb{G})$ is an homogeneous differential operator of degree $k$ in the horizontal derivatives for all $j$, $i$ and $k$.
Proof. By linearity, we can assume $\alpha = \alpha_j \theta_j^h$ for a fixed $j$. By (57),

$$\alpha \rightarrow d \Pi_E \alpha$$

$$= \sum_{k=0}^{N_{\max}^{h+p}} \sum_{i \in I_{h+p}^k} \left( (dQ_{p,p+k,j,i}^h \alpha_j) \wedge \theta_i^h + (Q_{p,p+k,j,i}^h \alpha_j) d\theta_i^h \right)$$

$$= \sum_{k=0}^{N_{\max}^{h+p}} \sum_{i \in I_{h+p}^k} \left( \sum_s \left( W_s Q_{p,p+k,j,i}^h \alpha_j \right) \theta_s \wedge \theta_i^h + (Q_{p,p+k,j,i}^h \alpha_j) d\theta_i^h \right).$$

Obviously, $\theta_s \wedge \theta_i^h \in \Theta^{h+1,w(\theta_j)+p+k}$ and $W_s Q_{p,p+k,j,i}^h$ is an homogenous differential operator in the horizontal derivatives of order $w(\theta_j) + k$, and hence $(W_s Q_{p,p+k,j,i}^h \alpha_j) \theta_s \wedge \theta_i^h$ has the form $(\tilde{Q}_{p,p+k',j,i}^h \alpha_j) \theta_i^{h+1}$, with $i \in I_{p+k'}$.

In addition, by Lemma 2.8, $d\theta_i^h$ is a linear combinations of elements in $\Theta^{h+1,p+k}$. Since $Q_{p,p+k,j,i}^h$ has order $k$, the lemma is completely proved. □

Proof of Proposition 7.1. By linearity, we can assume $\alpha = \sum_{j \in I_{h+1}^0} \alpha_j \xi_j^h$ for a fixed $p$. Since $\Xi^h$ and $\Theta^h$ are left invariant basis, there exist real constants $c_{j,\lambda}^h$ such that we can write

$$\alpha = \sum_{\lambda \in I_p^h} \sum_{j \in I_{h+1}^0} \left( \sum_{\xi} c_{j,\lambda}^h \alpha_j \right) \theta_{\lambda}^h := \sum_{\lambda \in I_p^h} \tilde{\alpha}_\lambda \theta_{\lambda}^h.$$ 

We notice first that, if $\beta \in \Lambda^{h+1} g$, then

$$\Pi_{E_{\alpha}^{h+1}} \beta = \sum_{q=M_{\min}^{h+1}}^{M_{\max}^{h+1}} \sum_{i \in I_{h+1}^q} \langle \beta, \xi_i^{h+1} \rangle \xi_i^{h+1}. \tag{59}$$

Replacing (58) in (59), we get

$$d_c \alpha = \Pi_{E_0} d \Pi_E \sum_{\lambda \in I_p^h} \tilde{\alpha}_\lambda \theta_{\lambda}^h$$

$$= \sum_{q=M_{\min}^{h+1}}^{M_{\max}^{h+1}} \sum_{i \in I_{h+1}^q} \sum_{\lambda \in I_p^h} \sum_{k=0}^{N_{\max}^{h+p}} \sum_{\ell \in I_{h+1}^{p+k}} \langle \tilde{Q}_{p,p+k,\lambda,\ell}^h (\alpha) \theta_{\lambda}^h, \theta_i^{h+1} \rangle \langle \xi_i^{h+1}, \xi_i^{h+1} \rangle.$$ 

We notice now that

$$c_{i,\ell}^{h+1} := \langle \theta_{\ell}^{h+1}, \xi_i^{h+1} \rangle \neq 0 \quad \text{only if} \quad q = p + k,$$

by Remark 2.6, that in turn is possible only if $q \geq p$. Moreover, by Remark 2.18, necessarily $q > p$. Thus the sum with respect to the index $k$ reduces to the only term $k = q - p$ (we point out that $0 \leq q - p \leq M_{\max}^{h+1} - p \leq N_{\max}^{h+1} - p$, since $M_{\max}^{h+1}$ is the highest weight in $E_{0}^{h+1} \subset \Lambda^{h+1} g$, whereas $N_{\max}^{h+1}$ is the highest weight in $\Lambda^{h+1} g$).

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Thus (60) becomes
\[
d_{\epsilon_{\alpha}} = \sum_{q=\max\{p+1,M_{m+1}\}}^{M_{m+1}} \sum_{i \in \mathcal{I}} \sum_{\lambda \in \mathcal{H}_{q}} \left( d_{q+1}^{h+1} \tilde{Q}_{p,q,\lambda,\ell} \tilde{\alpha}_{\lambda} \right) \varepsilon_{q+1}^{h+1}
\]
(61)
\[
d_{\epsilon_{\alpha}} = \sum_{q=\max\{p+1,M_{m+1}\}}^{M_{m+1}} \sum_{j \in \mathcal{I}} \left( P_{p,q,j,\ell}^{h} \alpha_{j} \right) \varepsilon_{q+1}^{h+1},
\]
where
\[
P_{h}^{p,q,j,\ell} := \sum_{\lambda \in \mathcal{H}_{q}} \sum_{\ell,\ell' \in \mathcal{H}_{q}} c_{j,\lambda}^{h+1} \tilde{Q}_{p,q,\lambda,\ell}^{h}
\]
is an homogeneous polynomial of degree \( q - p \) in the horizontal derivatives.

\( \square \)

We give now some explicit examples of the classes \( E_{0}^{*} \) for some significant groups.

Example 7.4. First of all, we stress that in any Carnot group \( \mathcal{G} \) the space \( E_{0}^{1} \) consists precisely of all horizontal forms, i.e. of all forms of weight 1. Indeed, notice first that on 0-forms \( d_{0} = 0 \). On the other hand, if \( X_{i}, X_{j} \) are left invariant vector fields, and \( \theta_{\ell} \in \Theta_{1} \), by the identity
\[
d_{0} \theta_{\ell}(X_{i}, X_{j}) = d \theta_{\ell}(X_{i}, X_{j}) = -\theta_{\ell}([X_{i}, X_{j}]),
\]
it follows that \( d_{0} \theta_{\ell} = 0 \) if and only if \( \theta_{\ell} \) has weight one, since \([X_{i}, X_{j}]\) belongs to \( V_{2} \oplus \cdots \oplus V_{\kappa} \).

Example 7.5. Let \( \mathcal{G} := \mathbb{H}^{1} \equiv \mathbb{R}^{3} \) be the first Heisenberg group, with variables \((x, y, t)\). Set \( X := \partial_{x} + 2y \partial_{t}, \ Y := \partial_{y} - 2x \partial_{t}, \ T := \partial_{t} \). We have \( X^{2} = dx, \ Y^{2} = dy, \ T^{2} = \theta \) (the contact form of \( \mathbb{H}^{1} \)). The stratification of the algebra \( \mathfrak{g} \) is given by \( \mathfrak{g} = V_{1} \oplus V_{2} \), where \( V_{1} = \text{span} \{X, Y\} \) and \( V_{2} = \text{span} \{T\} \). In this case
\[
E_{0}^{1} = \text{span} \{dx, dy\};
E_{0}^{2} = \text{span} \{dx \wedge \theta, dy \wedge \theta\};
E_{0}^{3} = \text{span} \{dx \wedge dy \wedge \theta\}.
\]
Moreover
\[
d_{\epsilon}(\alpha_{1} dx + \alpha_{2} dy)
\]
\[= \Pi_{E_{0}} d(\alpha_{1} dx + \alpha_{2} dy - \frac{1}{4}(X\alpha_{2} - Y\alpha_{1})\theta)
\]
\[= D(\alpha_{1} dx + \alpha_{2} dy),
\]
where \( D \) is the second order differential of horizontal 1-forms in \( \mathbb{H}^{1} \) that has the form
\[
D(\alpha_{1} dx + \alpha_{2} dy)
\]
\[= -\frac{1}{4}(X^{2}\alpha_{2} - 2XY\alpha_{1} + YX\alpha_{1})dx \wedge \theta - \frac{1}{4}(2YX\alpha_{2} - Y^{2}\alpha_{1} - XY\alpha_{2})dy \wedge \theta
\]
\[:= P_{1}(\alpha_{1}, \alpha_{2}) dx \wedge \theta + P_{2}(\alpha_{1}, \alpha_{2}) dy \wedge \theta.
\]
On the other hand, if
\[ \alpha = +\alpha_{13}dx \wedge \theta + \alpha_{23}dy \wedge \theta \in E_0^2, \]
then
\[ d_c\alpha = (X\alpha_{23} - Y\alpha_{13}) \ dx \wedge dy \wedge \theta. \]

**Example 7.6.** Let \( G := H^1 \times \mathbb{R} \), and denote by \((x, y, t)\) the variables in \( H^1 \) and by \( s \) the variable in \( \mathbb{R} \). Set \( X, Y, T \) as above, and \( S := \partial_s \). We have \( X^2 = dx, Y^2 = dy, S^2 = ds, T^2 = \theta \). The stratification of the algebra \( g \) is given by \( g = V_1 \oplus V_2 \), where \( V_1 = \text{span} \{X, Y, S\} \) and \( V_2 = \text{span} \{T\} \). In this case
\[
E_0^1 = \text{span} \{dx, dy, ds\}; \\
E_0^2 = \text{span} \{dx \wedge ds, dy \wedge ds, dx \wedge \theta, dy \wedge \theta\}; \\
E_0^3 = \text{span} \{dx \wedge dy \wedge \theta, dx \wedge ds \wedge \theta, dy \wedge ds \wedge \theta\}.
\]
Moreover
\[
d_c(\alpha_1dx + \alpha_2dy + \alpha_3ds) \\
= D(\alpha_1dx + \alpha_2dy) + (X\alpha_3 - S\alpha_1)dx \wedge ds + (Y\alpha_3 - S\alpha_2)dy \wedge ds,
\]
where \( D \) is the second order differential of horizontal 1-forms in \( H^1 \) that has the form
\[ D(\alpha_1dx + \alpha_2dy) = P_1(\alpha_1, \alpha_2)dx \wedge \theta + P_2(\alpha_1, \alpha_2)dy \wedge \theta. \]

On the other hand, if
\[ \alpha = \alpha_{13}dx \wedge ds + \alpha_{23}dy \wedge ds + \alpha_{14}dx \wedge \theta + \alpha_{24}dy \wedge \theta \in E_0^2, \]
then
\[ d_c\alpha = (X\alpha_{23} - Y\alpha_{13}) \ dx \wedge dy \wedge \theta \\
+ (T\alpha_{13} - S\alpha_{14} - \frac{1}{4}(X^2\alpha_{23} - XY\alpha_{13})) \ dx \wedge ds \wedge \theta \\
+ (T\alpha_{23} - S\alpha_{24} - \frac{1}{4}(YX\alpha_{23} - Y^2\alpha_{13}))dy \wedge ds \wedge \theta. \]

**Example 7.7.** Let now \( G := H^2 \times \mathbb{R} \), and denote by \((x_1, x_2, y_1, y_2, t)\) the variables in \( H^2 \) and by \( s \) the variable in \( \mathbb{R} \). Set \( X_i := \partial_{x_i} + 2y_i\partial_t, Y_i := \partial_{x_i} - 2x_i\partial_t, i = 1, 2, T := \partial_t, \) and \( S := \partial_s \). We have \( X_i^2 = dx_i, Y_i^2 = dy_i, \ i = 1, 2, S^2 = ds, T^2 = \theta \) (the contact form of \( H^2 \)). The stratification of the algebra \( g \) is given by \( g = V_1 \oplus V_2 \), where \( V_1 = \text{span} \{X_1, X_2, Y_1, Y_2, S\} \) and \( V_2 = \text{span} \{T\} \).

Let us restrict ourselves to show the structure of the intrinsic differential on \( E_0^1 \), i.e. on horizontal 1-forms. Using the notations of (17), we can chose an orthonormal basis of \( \wedge^h g, h = 1, 2, 3 \) as follows:

- **h = 1:** \( \Theta^{1,1} = (\theta_{11}^1, \ldots, \theta_{11}^2) = (dx_1, dx_2, dy_1, dy_2, ds) \), and \( \Theta^{1,2} = (\theta_{01}^1) = (\theta) \).
- **h = 2:** \( \Theta^{2,2} = (\theta_{11}^1, \ldots, \theta_{10}^1) = (dx_1 \wedge dx_2, dy_1 \wedge dy_2, dx_1 \wedge dy_2, dx_1 \wedge dy_1, dx_1 \wedge dy_2, dx_2 \wedge \\
\quad dy_1, dx_2 \wedge dy_2, dx_1 \wedge ds, dx_2 \wedge ds, dy_1 \wedge ds, dy_2 \wedge ds), \Theta^{2,3} = (\theta_{11}^2, \ldots, \theta_{13}^2) = \\
\quad (dx_1 \wedge \theta, dx_2 \wedge \theta, dy_1 \wedge \theta, dy_2 \wedge \theta, ds \wedge \theta). \)
- **h = 3:** \( \Theta^{3,5} = (\theta_{11}^3, \ldots, \theta_{10}^3) = (dx_1 \wedge dx_2 \wedge dy_1, dx_1 \wedge dx_2 \wedge dy_2, dx_1 \wedge dx_2 \wedge \ldots \\
\quad dx_1 \wedge dy_1 \wedge dy_2, dx_1 \wedge dx_2 \wedge dy_1 \wedge dy_2, dx_1 \wedge dy_2 \wedge ds, dx_1 \wedge dy_2 \wedge ds, dx_2 \wedge dy_1 \wedge \\
\quad ds, dx_2 \wedge dy_1 \wedge ds, dy_2 \wedge ds) \). \( \Theta^{3,4} = (\theta_{11}^3, \ldots, \theta_{20}^3) = \\
\quad (dx_1 \wedge dx_2 \wedge \theta, dy_1 \wedge dy_2 \wedge \theta, dx_1 \wedge dy_1 \wedge \theta, dx_1 \wedge dy_2 \wedge \theta, dx_2 \wedge dy_1 \wedge \\
\quad \theta, dx_2 \wedge dy_2 \wedge \theta, dx_1 \wedge ds \wedge \theta, dy_1 \wedge ds \wedge \theta, dy_2 \wedge ds \wedge \theta). \)
We have:

\[ d_0 \theta^1_i = 0 \quad \text{when} \quad i = 1, \ldots, 5, \quad d_0 \theta^1_6 = 4(\theta^2_3 + \theta^2_6); \]
\[ d_0 \theta^2_i = 0 \quad \text{when} \quad i = 1, \ldots, 10, \quad d_0 \theta^2_1 = 4\theta^2_1, \quad d_0 \theta^2_2 = -4\theta^3_1, \]
\[ d_0 \theta^2_3 = -4\theta^3_6, \quad d_0 \theta^2_4 = 4\theta^3_4, \quad d_0 \theta^2_5 = 4(\theta^3_5 + \theta^3_{10}). \]

Thus

\[
M_1 = \begin{pmatrix}
0 & \ldots & 0 & 0 & -4 & 0 & 0 & 0 \\
0 & \ldots & 0 & 4 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 4 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 4 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

\[
M_2 = \begin{pmatrix}
0 & \ldots & 0 & 0 & -4 & 0 & 0 & 0 \\
0 & \ldots & 0 & 4 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 4 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 4 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

As usual, \( E_0^1 \) is the space of left invariant horizontal 1-forms, i.e. an orthonormal basis of \( E_0^1 \) is given by \( \{dx_1, dx_2, dy_1, dy_2, ds\} \). Keeping into account that \( E_0^2 \) can be identified with \( \ker M_2 \cap \ker^l M_1 \), then the left invariant form \( \alpha = \sum_j \alpha_j \theta^2_j \) belongs to \( E_0^2 \) if and only if

\[ \alpha_6 = -\alpha_3 \]

and

\[ \alpha_{11} = \alpha_{12} = \alpha_{13} = \alpha_{14} = \alpha_{15} = 0. \]

Hence an orthonormal basis of \( E_0^2 \) is given by \( \xi^2_1, \xi^2_2, \frac{1}{\sqrt{2}}(\xi^2_3 - \xi^2_6), \xi^2_4, \xi^2_5, \xi^2_7, \xi^2_8, \xi^2_9, \xi^2_{10} \) \( = \{dx_1 \wedge dx_2, dy_1 \wedge dy_2, \frac{1}{\sqrt{2}}(dx_1 \wedge dy_1 - dx_2 \wedge dy_2), dx_1 \wedge dy_2, dx_2 \wedge dy_1, dx_1 \wedge ds, dx_2 \wedge ds, dy_1 \wedge ds, dy_2 \wedge ds\} \). In particular, the orthogonal projection \( \Pi_{E_0} \alpha \) of \( \alpha \) on \( E_0 \) has the form

\[ \Pi_{E_0} \alpha = \sum_{j=1}^{10} \alpha_j \xi^2_j + \frac{\alpha_3 - \alpha_6}{2}(\xi^2_3 - \xi^2_6). \]
We want now to write explicitly $d_c$ acting on forms $\alpha = \alpha(x) = \sum_{j=1}^{5} \alpha_j(x) \xi_j$. To this end, let us write first $\Pi_{E^1} \alpha$. Because of the structure of $\wedge^1 g$, by Proposition 2.17,

$$\Pi_{E^1} \alpha = \alpha + \gamma \theta,$$

for a smooth function $\gamma$, with $\gamma \theta = -d_0^{-1}(d_1 \alpha)$, i.e.

$$d_0(\gamma \theta) + d_1 \alpha \in \ker \delta_0,$$

by Corollary 2.11. We can write (63) in the form

$$4 \gamma(dx_1 \wedge dy_1 + dx_2 \wedge dy_2)$$

$$+ (X_1 \alpha_2 - X_2 \alpha_1)dx_1 \wedge dx_2 + (Y_1 \alpha_4 - Y_2 \alpha_3)dy_1 \wedge dy_2$$

$$+ (X_1 \alpha_3 - Y_1 \alpha_1)dx_1 \wedge dy_1 + (X_1 \alpha_4 - Y_2 \alpha_1)dx_1 \wedge dy_2$$

$$+ (X_2 \alpha_3 - Y_1 \alpha_2)dx_2 \wedge dy_1 + (X_2 \alpha_4 - Y_2 \alpha_2)dx_2 \wedge dy_2$$

$$+ (X_1 \alpha_5 - S \alpha_1)dx_1 \wedge ds + (X_2 \alpha_5 - S \alpha_2)dx_2 \wedge ds,$$

$$+ (Y_1 \alpha_5 - S \alpha_3)dy_1 \wedge ds + (Y_2 \alpha_5 - S \alpha_4)dy_2 \wedge ds \in \ker \delta_0.$$

Because of the form of $^t M_1$ above, this gives

$$8 \gamma + X_1 \alpha_3 - Y_1 \alpha_1 + X_2 \alpha_4 - Y_2 \alpha_2 = 0,$$

i.e.

$$\gamma = -\frac{1}{8}(X_1 \alpha_3 - Y_1 \alpha_1 + X_2 \alpha_4 - Y_2 \alpha_2).$$

However, the explicit form of $\gamma$ does not matter in the final expression of $d_c \alpha$. Indeed, keeping in mind that $d_0 \alpha = 0$, and that $\Pi_{E_0}(d_1(\gamma \theta)) = \Pi_{E_0}(d_7 \gamma \wedge \theta) = 0$, and $\Pi_{E_0}(d_2(\alpha + \gamma \theta)) = 0$, since $\Pi_{E_0}$ vanishes on forms of weight 3, by our previous computation (64), we have

$$d_c \alpha = \Pi_{E_0}(d(\alpha + \gamma \theta))$$

$$= \Pi_{E_0}(d_0(\alpha + \gamma \theta) + d_1(\alpha + \gamma \theta)) + \Pi_{E_0}(d_2(\alpha + \gamma \theta))$$

$$= \Pi_{E_0}(d_0(\gamma \theta) + d_1 \alpha)$$

$$= \Pi_{E_0}((X_1 \alpha_2 - X_2 \alpha_1)dx_1 \wedge dx_2 + (Y_1 \alpha_4 - Y_2 \alpha_3)dy_1 \wedge dy_2$$

$$+ (X_1 \alpha_3 - Y_1 \alpha_1 + 4\gamma)dx_1 \wedge dy_1 + (X_1 \alpha_4 - Y_2 \alpha_1)dx_1 \wedge dy_2$$

$$+ (X_2 \alpha_3 - Y_1 \alpha_2)dx_2 \wedge dy_1 + (X_2 \alpha_4 - Y_2 \alpha_2 + 4\gamma)dx_2 \wedge dy_2$$

$$+ (X_1 \alpha_5 - S \alpha_1)dx_1 \wedge ds + (X_2 \alpha_5 - S \alpha_2)dx_2 \wedge ds,$$

$$+ (Y_1 \alpha_5 - S \alpha_3)dy_1 \wedge ds + (Y_2 \alpha_5 - S \alpha_4)dy_2 \wedge ds$$

$$+ (X_1 \alpha_2 - X_2 \alpha_1)dx_1 \wedge dx_2 + (Y_1 \alpha_4 - Y_2 \alpha_3)dy_1 \wedge dy_2$$

$$+ (X_1 \alpha_3 - Y_1 \alpha_1 - 4\gamma)dx_1 \wedge dy_1 + (X_1 \alpha_4 - Y_2 \alpha_1)dx_1 \wedge dy_2$$

$$+ (X_2 \alpha_3 - Y_1 \alpha_2)dx_2 \wedge dy_1 + (X_2 \alpha_4 - Y_2 \alpha_2 - 4\gamma)dx_2 \wedge dy_2$$

$$+ (X_1 \alpha_5 - S \alpha_1)dx_1 \wedge ds + (X_2 \alpha_5 - S \alpha_2)dx_2 \wedge ds,$$

$$+ (Y_1 \alpha_5 - S \alpha_3)dy_1 \wedge ds + (Y_2 \alpha_5 - S \alpha_4)dy_2 \wedge ds$$

$$+ \frac{X_1 \alpha_3 - Y_1 \alpha_4 - X_2 \alpha_4 + X_2 \alpha_2}{\sqrt{2}} 1 \frac{1}{\sqrt{2}}(dx_1 \wedge dy_1 - dx_2 \wedge dy_2),$$

by (62).
Example 7.8. Let $G \cong \mathbb{R}^6$ be the Carnot group associated with the vector fields

\[
\begin{align*}
X_1 & = \partial_1 \\
X_2 & = \partial_2 + x_1 \partial_4 \\
X_3 & = \partial_3 + x_2 \partial_5 + x_4 \partial_6
\end{align*}
\]

and

\[
\begin{align*}
X_4 & = \partial_4 \\
X_5 & = \partial_5 + x_1 \partial_6 \\
X_6 & = \partial_6.
\end{align*}
\]

Only non-trivial commutation rules are

\[
[X_1, X_2] = X_4, \quad [X_2, X_3] = X_5, \quad [X_1, X_5] = X_6, \quad [X_4, X_3] = X_6.
\]

The $X_j$'s are left invariant and coincide with the elements of the canonical basis of $\mathbb{R}^6$ at the origin. The Lie algebra $g$ of $G$ admits the stratification

\[
g = g_1 \oplus g_2 \oplus g_3,
\]

where $g_1 = \text{span} \{ X_1, X_2, X_3 \}$, $g_2 = \text{span} \{ X_4, X_5 \}$, and $g_3 = \text{span} \{ X_6 \}$.

We set also

\[
\begin{align*}
\theta_5 & = dx_5 - x_2 dx_3 \\
\theta_4 & = dx_4 - x_1 dx_2 \\
\theta_6 & = dx_6 - x_1 dx_5 + (x_1 x_2 - x_4) dx_3
\end{align*}
\]

and

\[
\begin{align*}
\theta_1 = dx_1, \quad \theta_2 = dx_2, \quad \theta_3 = dx_3.
\end{align*}
\]

Clearly

\[
\theta_i = X_i^2 \quad \text{for } i, j = 1, \ldots, 6.
\]

Moreover

\[
d\theta_4 = -\theta_1 \wedge \theta_2, \quad d\theta_5 = -\theta_2 \wedge \theta_3, \quad d\theta_6 = \theta_3 \wedge \theta_4 - \theta_1 \wedge \theta_5.
\]

As in Example 7.7, let us restrict ourselves to show the structure of the intrinsic differential on $E_0^6$, i.e. on horizontal 1-forms. Using the notations of (17), we can choose an orthonormal basis of $\bigwedge^h g$, $h = 1, 2, 3$ as follows:

- **h = 1**: $\Theta^{1,1} = \{ \theta_1, \theta_2, \theta_3 \}$, $\Theta^{1,2} = \{ \theta_4, \theta_5 \}$, and $\Theta^{1,3} = \{ \theta_6 \}$.

- **h = 2**: $\Theta^{2,2} = \{ \theta_1^2, \theta_2^2, \theta_3^2 \} = \{ \theta_1 \wedge \theta_2, \theta_1 \wedge \theta_3, \theta_2 \wedge \theta_3 \}$, $\Theta^{2,3} = \{ \theta_4^2, \ldots, \theta_6^2 \}$

  \[
  = \{ \theta_1 \wedge \theta_4, \theta_1 \wedge \theta_5, \theta_1 \wedge \theta_6, \theta_2 \wedge \theta_4, \theta_2 \wedge \theta_5, \theta_2 \wedge \theta_6, \theta_3 \wedge \theta_4, \theta_3 \wedge \theta_5, \theta_3 \wedge \theta_6 \},
  \]

  $\Theta^{2,4} = \{ \theta_4^3, \ldots, \theta_6^3 \}$

- **h = 3**: $\Theta^{3,3} = \{ \theta_1^3, \theta_2^3, \theta_3^3 \} = \{ \theta_1 \wedge \theta_2 \wedge \theta_3 \}$, $\Theta^{3,4} = \{ \theta_1^3, \ldots, \theta_6^3 \}$

  $\Theta^{3,5} = \{ \theta_1, \theta_2, \theta_3, \theta_1 \wedge \theta_2, \theta_1 \wedge \theta_3, \theta_2 \wedge \theta_3, \theta_4 \wedge \theta_5, \theta_4 \wedge \theta_6, \theta_5 \wedge \theta_6, \theta_4 \wedge \theta_5 \wedge \theta_6 \}$

  $\Theta^{3,6} = \{ \theta_4^4, \ldots, \theta_6^4 \}$

  $\Theta^{3,7} = \{ \theta_2^5 \} = \{ \theta_4 \wedge \theta_5 \wedge \theta_6 \}$.
We notice that an orthonormal basis of $\bigwedge^h \mathfrak{g}$, $h = 4, 5, 6$ can be obtained by Hodge duality.

We have

$$M_1 = \begin{pmatrix}
0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

As usual, $E_0^1$ is the space of left invariant horizontal 1-forms, i.e. an orthonormal basis of $E_0^1$ is given by $\{\theta_1, \theta_2, \theta_3\}$. Keeping into account that $E_0^2$ can be identified with $\ker M_2 \cap \ker^t M_1$, then the left invariant form $\alpha = \sum_j \alpha_j \theta_j^2$ belongs to $E_0^2$ if and only if

$$\alpha_5 = -\alpha_8, \quad \alpha_{10} = \alpha_{11} = \alpha_{12} = \alpha_{13} = \alpha_{14} = \alpha_{15} = 0$$

and

$$\alpha_5 = \alpha_8, \quad \alpha_3 = \alpha_1 = 0.$$

Therefore, an orthonormal basis $\{\xi_1^2, \ldots, \xi_5^2\}$ of $E_0^2 = E_0^{2,2} \oplus E_0^{2,3}$ is given by

$$\{\theta_1 \wedge \theta_3\} \cup \{\theta_1 \wedge \theta_4, \theta_2 \wedge \theta_4, \theta_2 \wedge \theta_5, \theta_3 \wedge \theta_5\}.$$
In particular, the orthogonal projection \( \Pi_{E_0} \alpha \) of \( \alpha \in \bigwedge^2 g \) on \( E_0^2 \) has the form

\[
\Pi_{E_0} \alpha = \alpha_2 \theta_1 \wedge \theta_3 + \alpha_4 \theta_1 \wedge \theta_4 + \alpha_6 \theta_2 \wedge \theta_4 + \alpha_7 \theta_2 \wedge \theta_5 + \alpha_9 \theta_3 \wedge \theta_5.
\]

We want now to write explicitly \( d_c \) acting on forms \( \alpha = \alpha(x) = \sum_{j=1}^{3} \alpha_j(x) \theta_j \). To this end, let us write first \( \Pi_{E_1} \alpha \). We have

\[
\Pi_{E_1} \alpha = (\Pi_{E_1} \alpha)_1 + (\Pi_{E_1} \alpha)_2 + (\Pi_{E_1} \alpha)_3
\]

\[
= \alpha + (\Pi_{E_1} \alpha)_2 + (\Pi_{E_1} \alpha)_3
\]

\[
:= \alpha + (\gamma_4 \theta_4 + \gamma_5 \theta_5) + \gamma_6 \theta_6,
\]

with

\[
\gamma_4 \theta_4 + \gamma_5 \theta_5 = -d_0^{-1}(d_1(\alpha_1 \theta_1 + \alpha_2 \theta_2 + \alpha_3 \theta_3))
\]

\[
= -d_0^{-1}((X_1 \alpha_2 - X_2 \alpha_1) \theta_1 \wedge \theta_2 + (X_1 \alpha_3 - X_3 \alpha_1) \theta_1 \wedge \theta_3
\]

\[
+ (X_2 \alpha_3 - X_3 \alpha_2) \theta_2 \wedge \theta_3),
\]

and

\[
\gamma_6 \theta_6 = -d_0^{-1}(d_1(\gamma_4 \theta_4 + \gamma_5 \theta_5) + d_2 \alpha)
\]

Now (66) is equivalent to

\[
d_0(\gamma_4 \theta_4 + \gamma_5 \theta_5) + (X_1 \alpha_2 - X_2 \alpha_1) \theta_1 \wedge \theta_2 + (X_1 \alpha_3 - X_3 \alpha_1) \theta_1 \wedge \theta_3
\]

\[
+ (X_2 \alpha_3 - X_3 \alpha_2) \theta_2 \wedge \theta_3 \in \ker^4 M_1,
\]

i.e.

\[
(-\gamma_4 + X_1 \alpha_2 - X_2 \alpha_1) \theta_1 \wedge \theta_2 + (X_1 \alpha_3 - X_3 \alpha_1) \theta_1 \wedge \theta_3
\]

\[
+ (-\gamma_5 + X_2 \alpha_3 - X_3 \alpha_2) \theta_2 \wedge \theta_3 \in \ker^4 M_1,
\]

that gives eventually

\[
\gamma_4 = X_1 \alpha_2 - X_2 \alpha_1 \quad \text{and} \quad \gamma_5 = X_2 \alpha_3 - X_3 \alpha_2
\]
Consider now (67), that is equivalent to
\[
d_0(\gamma_6 \theta_6) + d_1((X_1 \alpha_2 - X_2 \alpha_1) \theta_4 + (X_2 \alpha_3 - X_3 \alpha_2) \theta_5 + d_2 \alpha)
\]
\[= \gamma_6(\theta_3 \wedge \theta_4 - \theta_1 \wedge \theta_5) + X_1(X_1 \alpha_2 - X_2 \alpha_1) \theta_1 \wedge \theta_4
\]
\[+ X_2(X_1 \alpha_2 - X_2 \alpha_1) \theta_2 \wedge \theta_4
\]
\[+ X_3(X_1 \alpha_2 - X_2 \alpha_1) \theta_3 \wedge \theta_4 + X_1(X_2 \alpha_3 - X_3 \alpha_2) \theta_1 \wedge \theta_5
\]
\[+ X_2(X_2 \alpha_3 - X_3 \alpha_2) \theta_2 \wedge \theta_5
\]
\[+ X_3(X_2 \alpha_3 - X_3 \alpha_2) \theta_3 \wedge \theta_5 - X_4 \alpha_1 \theta_1 \wedge \theta_4
\]
\[- X_4 \alpha_2 \theta_2 \wedge \theta_4 - X_4 \alpha_3 \theta_3 \wedge \theta_4 - X_5 \alpha_1 \theta_1 \wedge \theta_5
\]
\[- X_5 \alpha_2 \theta_2 \wedge \theta_5 - X_5 \alpha_3 \theta_3 \wedge \theta_5
\]
\[= X_1(X_1 \alpha_2 - X_2 \alpha_1) \theta_1 \wedge \theta_4 + X_2(X_1 \alpha_2 - X_2 \alpha_1) \theta_2 \wedge \theta_4
\]
\[+ (X_3(X_1 \alpha_2 - X_2 \alpha_1) + \gamma_6) \theta_3 \wedge \theta_4 + (X_1(X_2 \alpha_3 - X_3 \alpha_2) - \gamma_6) \theta_1 \wedge \theta_5
\]
\[+ X_2(X_2 \alpha_3 - X_3 \alpha_2) \theta_2 \wedge \theta_5
\]
\[+ X_3(X_2 \alpha_3 - X_3 \alpha_2) \theta_3 \wedge \theta_5 - X_4 \alpha_1 \theta_1 \wedge \theta_4
\]
\[- X_4 \alpha_3 \theta_3 \wedge \theta_4 - X_5 \alpha_1 \theta_1 \wedge \theta_5
\]
\[- X_5 \alpha_2 \theta_2 \wedge \theta_5 - X_5 \alpha_3 \theta_3 \wedge \theta_5
\]
\[= (X_1(X_1 \alpha_2 - X_2 \alpha_1) - X_4 \alpha_1) \theta_1^2 + (X_1(X_2 \alpha_3 - X_3 \alpha_2) - \gamma_6 - X_5 \alpha_1) \theta_5^2
\]
\[+ (X_2(X_1 \alpha_2 - X_2 \alpha_1) - X_4 \alpha_2) \theta_2^2 + (X_2(X_2 \alpha_3 - X_3 \alpha_2) - X_5 \alpha_2) \theta_5^2
\]
\[+ (X_3(X_1 \alpha_2 - X_2 \alpha_1) + \gamma_6 - X_4 \alpha_3) \theta_3^2 + (X_3(X_2 \alpha_3 - X_3 \alpha_2) - X_5 \alpha_3) \theta_5^2
\]
\[\in \ker 'M_1
\]
i.e. to
\[X_1(X_2 \alpha_3 - X_3 \alpha_2) - \gamma_6 - X_5 \alpha_1 - (X_3(X_1 \alpha_2 - X_2 \alpha_1) + \gamma_6 - X_4 \alpha_3) = 0
\]
This yields
\[\gamma_6 = \frac{1}{2} (X_1(X_2 \alpha_3 - X_3 \alpha_2) - X_5 \alpha_1 - X_3(X_1 \alpha_2 - X_2 \alpha_1) + X_4 \alpha_3).
\]
Thus
\[\Pi_{E^1} \alpha = \alpha_1 \theta_1 + \alpha_2 \theta_2 + \alpha_3 \theta_3
\]
\[+ (X_1 \alpha_2 - X_2 \alpha_1) \theta_4 + (X_2 \alpha_3 - X_3 \alpha_2) \theta_5
\]
\[+ \frac{1}{2} (X_1(X_2 \alpha_3 - X_3 \alpha_2) - X_5 \alpha_1 - X_3(X_1 \alpha_2 - X_2 \alpha_1) + X_4 \alpha_3) \theta_6.
\]
Then
\[d \alpha = (X_1 \alpha_3 - X_3 \alpha_1) \theta_1 \wedge \theta_3 + (X_1(X_1 \alpha_2 - X_2 \alpha_1) - X_4 \alpha_1) \theta_1 \wedge \theta_4
\]
\[+ (X_2(X_1 \alpha_2 - X_2 \alpha_1) - X_4 \alpha_2) \theta_2 \wedge \theta_4
\]
\[+ (X_2(X_2 \alpha_3 - X_3 \alpha_2) - X_5 \alpha_2) \theta_2 \wedge \theta_5
\]
\[+ (X_3(X_2 \alpha_3 - X_3 \alpha_2) - X_5 \alpha_3) \theta_3 \wedge \theta_5.
\]

**Example 7.9.** Let \( G = (\mathbb{R}^4, \cdot) \) be the Carnot group whose Lie algebra is \( \mathfrak{g} = V_1 \oplus V_2 \oplus V_3 \) with \( V_1 = \text{span} \{X_1, X_2\}, \ V_2 = \text{span} \{X_3\}, \) and \( V_3 = \text{span} \{X_4\}, \) the only non zero commutation relations being
\[ [X_1, X_2] = X_3, \quad [X_1, X_3] = X_4. \]
The group $G$ is called Engel group. In exponential coordinates an explicit representation of the vector fields is

$$X_1 = \partial_1 - \frac{x_2}{2} \partial_3 - (\frac{x_3}{2} + \frac{x_1 x_2}{12}) \partial_4 , 
X_2 = \partial_2 + \frac{x_1}{2} \partial_3 + \frac{x_1^2}{12} \partial_4 

X_3 = \partial_3 + \frac{x_1}{2} \partial_4 , 
X_4 = \partial_4.$$ 

Denote by $\theta_1, \ldots, \theta_4$ the dual left invariant forms. The following result is proved in [25]: as in Remark 7.4, an orthonormal basis of $\text{E}^{\text{v}}_{\text{G}}$ is given by $\{\theta_1, \theta_2\}$: an orthonormal basis of $E_0^2 = E_{0,0}^{2,3} \oplus E_{0,0}^{2,4}$ is given by $\{\theta_2 \wedge \theta_3\} \cup \{\theta_1 \wedge \theta_4\}$. Moreover, bases of $E_0^3, E_0^4$ can be written by Hodge duality.

If $\alpha = \alpha_1 \theta_1 + \alpha_2 \theta_2 \in E_1^1$, then

$$d_c \alpha = (X_2(X_1 \alpha_2 - X_2 \alpha_1) - X_3 \alpha_2) \theta_2 \wedge \theta_3 + (X_1(X_3 \alpha_2 - (X_1 X_2 + X_3) \alpha_1) - X_4 \alpha_1) \theta_1 \wedge \theta_4.$$ 

Example 7.10. Let us consider now the free group $G$ of step 3 with 2 generators, i.e. the Carnot group whose Lie algebra is $\mathfrak{g} = V_1 \oplus V_2 \oplus V_3$ with $V_1 = \text{span} \{X_1, X_2\}$, $V_2 = \text{span} \{X_3\}$, and $V_3 = \text{span} \{X_4, X_5\}$, the only non zero commutation relations being

$$[X_1, X_2] = X_3 \quad , \quad [X_1, X_3] = X_4 \quad , \quad [X_2, X_3] = X_5.$$ 

In exponential coordinates, the group $G$ can be identified with $\mathbb{R}^5$, and an explicit representation of the vector fields is

$$X_1 = \partial_1 \quad , \quad X_2 = \partial_2 + x_1 \partial_3 + \frac{x_1^2}{2} \partial_4 + x_1 x_2 \partial_5 

X_3 = \partial_3 + x_1 \partial_4 + x_2 \partial_5 \quad , \quad X_4 = \partial_4 \quad , \quad X_5 = \partial_5.$$ 

Denote by $\theta_1, \ldots, \theta_5$ the dual left invariant forms. As in Remark 7.4, an orthonormal basis of $E_0^1$ is given by $\{\theta_1, \theta_2\}$.

We have $d\theta_1 = d\theta_2 = 0$ and

$$d\theta_3 = -\theta_1 \wedge \theta_2, \quad d\theta_4 = -\theta_1 \wedge \theta_3, \quad d\theta_5 = -\theta_2 \wedge \theta_3.$$ 

Using the notations of (17), we can chose an orthonormal basis of $\land^h \mathfrak{g}$, $h = 1, 2, 3$ as follows:

**h = 1:** $\Theta^{1,1} = \{\theta_1, \theta_2\}$, $\Theta^{1,2} = \{\theta_3\}$, and $\Theta^{1,3} = \{\theta_4, \theta_5\}$.

**h = 2:** $\Theta^{2,2} = \{\theta_2^2\} = \{\theta_1 \wedge \theta_2\}$, $\Theta^{2,3} = \{\theta_2^3\} = \{\theta_1 \wedge \theta_3, \theta_2 \wedge \theta_3\}$, $\Theta^{2,4} = \{\theta_2^4\} = \{\theta_1 \wedge \theta_4, \theta_3 \wedge \theta_5\}$, $\Theta^{2,5} = \{\theta_2^5\} = \{\theta_4 \wedge \theta_5\}$, $\Theta^{2,6} = \{\theta_2^6\} = \{\theta_4 \wedge \theta_3\}$.

**h = 3:** $\Theta^{3,1} = \{\theta_1^1\} = \{\theta_1 \wedge \theta_2 \wedge \theta_3\}$, $\Theta^{3,5} = \{\theta_2^3\} = \{\theta_1 \wedge \theta_2 \wedge \theta_4, \theta_1 \wedge \theta_2 \wedge \theta_5\}$, $\Theta^{3,6} = \{\theta_2^4\} = \{\theta_1 \wedge \theta_3 \wedge \theta_4, \theta_1 \wedge \theta_3 \wedge \theta_5\}$, $\Theta^{3,7} = \{\theta_3^3\} = \{\theta_2 \wedge \theta_3 \wedge \theta_4, \theta_2 \wedge \theta_3 \wedge \theta_5, \theta_2 \wedge \theta_3 \wedge \theta_6\}$, $\Theta^{3,8} = \{\theta_3^4\} = \{\theta_3 \wedge \theta_4 \wedge \theta_5, \theta_2 \wedge \theta_4 \wedge \theta_5\}$.
We notice that an orthonormal basis of $\bigwedge^h g$, $h = 4, 5$ can be obtained by Hodge duality. We have

$$M_1 = \begin{pmatrix}
0 & 0 & -1 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}.$$  

Thus, if $\alpha = \alpha_1 \theta_1^2 + \cdots + \alpha_{10} \theta_{10}^2 \in E_0^2$, then

$$\alpha \in \ker^t M_1 \iff \alpha_1 = \alpha_2 = \alpha_3 = 0.$$  

Moreover

$$M_2 = \begin{pmatrix}
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix},$$

that yields

$$\alpha \in \ker M_2 \iff \alpha_5 = \alpha_6, \alpha_8 = \alpha_9 = \alpha_{10} = 0.$$  

Thus, an orthonormal basis of $E_0^2$ is given by

$$\{\theta_1^2, \frac{1}{\sqrt{2}}(\theta_5^2 + \theta_6^2), \theta_{10}^2\}.$$  

We want to show how $d_c$ acts on 1-forms $\alpha = \alpha_1 \theta_1 + \alpha_2 \theta_2 \in E_0^1$. To this end, let us write $\Pi_E \alpha = \alpha + \gamma_3 \theta_3 + \gamma_4 \theta_4 + \gamma_5 \theta_5$. We apply Proposition 2.17. We get first

$$\gamma_3 \theta_3 = -d_0^{-1}(d_1 \alpha) = -d_0^{-1}((X_1 \alpha_2 - X_2 \alpha_1) \theta_1 \land \theta_2),$$

i.e.

$$-\gamma_3 \theta_1 \land \theta_2 + (X_1 \alpha_2 - X_2 \alpha_1) \theta_1 \land \theta_2$$

$$= d_0(\gamma_3 \theta_3) + (X_1 \alpha_2 - X_2 \alpha_1) \theta_1 \land \theta_2 \in \ker^t M_1.$$  

Therefore

$$\gamma_3 = X_1 \alpha_2 - X_2 \alpha_1.$$  

Analogously,

$$\gamma_4 \theta_4 + \gamma_5 \theta_5 = -d_0^{-1}(d_1(\gamma_3 \theta_3) + d_2 \alpha).$$
This gives
\[ \gamma_4 = X_1^2 \alpha_2 - X_1 X_2 \alpha_1 - X_3 \alpha_1, \]
\[ \gamma_5 = X_2 X_1 \alpha_2 - X_2^2 \alpha_1 - X_3 \alpha_2. \]
Eventually, we get
\[ d_c \alpha = (X_1 \gamma_4 - X_4 \alpha_1) \theta_1 \wedge \theta_4 + (X_2 \gamma_5 - X_5 \alpha_2) \theta_2 \wedge \theta_5 \]
\[ + \frac{1}{2} (X_1 \gamma_5 - X_5 \alpha_1 + X_2 \gamma_4 - X_4 \alpha_2)(\theta_1 \wedge \theta_5 + \theta_2 \wedge \theta_4). \]

**Remark 7.11.** It is worth of noticing that Examples 7.5 and 7.10 show that, if \( G \) is a free group with 2 generators of step 2 and 3, all classes of intrinsic forms have pure weight (0,1,3,4 for the step 2 group, and 0,1,4,6,9,10 for the step 3 group). This phenomenon could suggest some special feature of free groups with respect to the weights of intrinsic forms (like, for instance, that in free groups all forms in \( E_0^* \) have pure weight). Unfortunately, this assertion fails to hold, at least in this naive form. Indeed, A. Ottazzi [20] showed us a counterexample for \( E_0^3 \) in the free group of step 2 with 3 generators. In fact, this a general phenomenon, due to the fact that for this case \( n = 6 \) (even), so that \( E_0^3 = *E_0^3 \), but \( Q = 9 \) (odd), yielding a contradiction with \( w(*) = w(\alpha) \), since \( w(*) = Q - w(\alpha) \). Clearly, this situation occurs whenever \( n \) is even and \( Q \) is odd.

**References**


