Periods of join algebraic cycles [1]

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Abstract

We determine the cycle class of join algebraic cycles inside smooth hypersurfaces by means of their periods. We show that being a join algebraic cycle is equivalent to have its associated Artin Gorenstein algebra isomorphic to the tensor product of the Artin Gorenstein algebras of each generating cycle. We use the join decomposition to study the presence of fake linear cycles in smooth hypersurfaces of the projective space. Our method allows us to reduce ourselves to study 0-dimensional fake linear cycles inside hypersurfaces of $\mathbb{P}^1$ with all their closed points defined over $\mathbb{Q}$. In consequence, we show that for any (n,d), there are infinitely many non-isomorphic smooth hypersurfaces of dimension n and degree d containing infinitely many fake linear cycles.

1 Introduction

Let $\mathbb{P}^{n+1}$ be an odd dimensional projective space (i.e. n even), and consider two odd dimensional (i.e. k is also even) linear subspaces $\mathbb{P}^{k+1}, \mathbb{P}^{n-k-1} \subseteq \mathbb{P}^{n+1}$ such that $\mathbb{P}^{k+1} \cap \mathbb{P}^{n-k-1} = \varnothing$. Assume $X_1 := \{f(x) = 0\} \subseteq \mathbb{P}^{k+1}$ and $X_2 := \{g(y) = 0\} \subseteq \mathbb{P}^{n-k-1}$ are two degree d smooth hypersurfaces, then

$$X := \{f(x) + g(y) = 0\} \subseteq \mathbb{P}^{n+1}$$

is also a smooth degree d hypersurface. Given two half dimensional algebraic subvarieties $Z_1 \subseteq X_1$ and $Z_2 \subseteq X_2$, their *join* $J(Z_1, Z_2) \subseteq X$ is the closure of the union of all lines connecting one point of Z_1 with one point of Z_2 inside $\mathbb{P}^{n+1}$. In other words, in terms of their homogeneous coordinate rings

$$S(J(Z_1,Z_2)) = \frac{\mathbb{C}[x,y]}{I(J(Z_1,Z_2))} = \frac{\mathbb{C}[x]}{I(Z_1)} \otimes \frac{\mathbb{C}[y]}{I(Z_2)} = S(Z_1) \otimes S(Z_2),$$

or equivalently in terms of their affine cones

$$C(J(Z_1,Z_2)) = C(Z_1) \times C(Z_2).$$

The above definition is compatible with rational equivalence and so, it can be extended bilinearly to a map

$$J : \mathrm{CH}^{\frac{k}{2}}(X_1) \otimes \mathrm{CH}^{\frac{n-k-2}{2}}(X_2) \to \mathrm{CH}^{\frac{n}{2}}(X).$$

This is a classical construction in algebraic geometry. A natural question is to ask what is the relation between the cycle classes of Z_1, Z_2 and $J(Z_1,Z_2)$. Our main result establishes that relation in terms of Griffiths' basis. Recall that by Griffiths' theorem [4] we can always write the primitive part of the cycle class of an algebraic cycle $Z \in \mathrm{CH}^{\frac{n}{2}}(X)$ inside a smooth degree d hypersurface $X = \{F = 0\} \subseteq \mathbb{P}^{n+1}$ of even dimension n as a residue form

$$[Z]_{\mathrm{prim}} = \frac{(-1)^{\frac{n}{2}+1}\frac{n}{2}!}{d}\mathrm{res}\left(\frac{P_Z\Omega}{F^{\frac{n}{2}+1}}\right)^{\frac{n}{2},\frac{n}{2}} \quad (1)$$

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for a unique $P_Z \in R^F_{(d-2)(\frac{n}{2}+1)}$. In consistency with the main result of [16] we say P_Z is the *polynomial associated* to the algebraic cycle Z. Using this notation we can state our main result as follows:

Theorem 1.1. Let $Z_1 \in \mathrm{CH}^{\frac{k}{2}}(X_1)$ and $Z_2 \in \mathrm{CH}^{\frac{n-k-2}{2}}(X_2)$, then $J(Z_1, Z_2) \in \mathrm{CH}^{\frac{n}{2}}(X)$ satisfies

$$P_{J(Z_1,Z_2)} = P_{Z_1} \cdot P_{Z_2}. \tag{2}$$

Furthermore, if $\delta \in H^{\frac{n}{2},\frac{n}{2}}(X, \mathbb{Q})_{\mathrm{prim}}$ then

$$R^{f+g,\delta} = R^{f,[Z_1]} \otimes R^{g,[Z_2]} \iff \delta = c \cdot [J(Z_1, Z_2)]_{\mathrm{prim}} \quad \text{for some } c \in \mathbb{Q}^{\times}. \tag{3}$$

Where $R^{f,[Z_1]}$, $R^{g,[Z_2]}$ and $R^{f+g,\delta}$ are the Artinian Gorenstein algebras associated to each Hodge cycle (see Definition 2.2).

This result can be stated in an equivalent way purely in terms of periods (see Theorem 3.1), which is in principle a purely topological relation and can be deduced as an application of a theorem of Sebastiani and Thom [15] which states that the monodromy of $f(x) + g(y) : \mathbb{C}^{n+2} \to \mathbb{C}$ splits as a tensor product of the monodromies of $f : \mathbb{C}^{k+2} \to \mathbb{C}$ and $g : \mathbb{C}^{n-k} \to \mathbb{C}$. In order to obtain the relation one has to identify the monodromy invariant part of the cohomology of the affine smooth fiber with the primitive cohomology of the projective hypersurface, keeping track of the isomorphisms in homology and the compatibility with the Griffiths' bases. In this purely algebraic context, we will give an alternative proof which relies in a toric birational modification of the ambient space which reduces the computation to a smooth hypersurface of a projective simplicial toric variety, and then use tools recently developed by the second author in [18] to describe residue forms along hypersurfaces in toric ambient.

After understanding the cycle class of a join of two algebraic cycles in terms of the cycle classes of each of them, it is natural to ask if this allows us to relate their corresponding Hodge loci. Recall that given a Hodge cycle $\delta \in H^{\frac{n}{2},\frac{n}{2}}(X, \mathbb{Q})$ we can consider $X = X_{t_0}$ as the central element of the family $\pi : \mathcal{X} \to T$ of all smooth degree d hypersurfaces of even dimension n of $\mathbb{P}^{n+1}$. Then in any small simply connected analytic neighbourhood of t_0 we can do a parallel transport of $\delta = \delta_{t_0}$ to $\delta_t \in H^n(X_t, \mathbb{Q})$ for $t \in (T, t_0)$ and consider the *Hodge locus* to be the germ of analytic subvariety

$$V_\delta := \{t \in (T, t_0) : \delta_t \in H^{\frac{n}{2},\frac{n}{2}}(X_t, \mathbb{Q})\}. \tag{4}$$

In fact, the Hodge locus comes with a natural analytic scheme structure which might be non-reduced. This non-reduceness might be detected for instance using the quadratic fundamental form introduced by Maclean (see [7]), which must vanish when the Hodge locus is smooth. We relate the quadratic fundamental form of the Hodge loci $V_{[Z_1]}$, $V_{[Z_2]}$ and $V_{[J(Z_1,Z_2)]}$ (see Theorem 4.1), and illustrate how the join description can be used to determine the Artinian Gorenstein ideal associated to some combinations of linear cycles in Fermat varieties and their quadratic fundamental forms in Section 5.

Our main motivation to study the periods of join algebraic cycles is to describe algebraic representatives of fake linear cycles in Fermat varieties of degree 3, 4 and 6, which were discovered by the authors in the previous article [2]. These cycles presented quite unexpected properties, such as being algebraic cycles not generated by their periods (in the sense of Movasati-Sertöz [11]), and the Zariski tangent space of their associated Hodge loci has codimension equal to $\binom{\frac{n}{2}+d}{d} - (\frac{n}{2}+1)^2$, which is conjecturally the smallest possible codimension of a Hodge locus, and is also conjectured to be attained only by linear cycles. The conjecture (which remains widely open) is supported in the classical results of Green [3] and Voisin [19] which prove the case of surfaces in $\mathbb{P}^3$, while for higher dimensions Otwinowska [13] establishes the result for $d >> n$, and the results of Movasati [8] together with [17] prove the conjecture for Hodge loci passing through the Fermat variety for $d \geq 2 + \frac{6}{n}$ and $d \neq 3, 4, 6$. The methods used in all the aforementioned articles rely on the bound of the codimension of the Zariski tangent space of the Hodge loci. This led Movasati to conjecture, originally only at the Fermat variety [9, Conjecture 18.8], that for $d \geq 2+\frac{6}{n}$ the Hodge loci attaining the mentioned bound at the level of the Zariski tangent space are only the Hodge loci of linear cycles. Movassati's conjecture was shown by second author in [17] for degrees $d \neq 3, 4, 6$. The authors [2] disproved Movasati's conjecture for all Fermat varieties of degree $d = 3, 4, 6$ by showing the existence of fake linear cycles. In that work the authors described the primitive cohomology class of fake linear cycles in terms of Griffiths' basis and the Galois action in cohomology, but the supporting algebraic representative remained unknown. The totally decomposed structure of the cohomology class of fake linear cycles (see [2, Theorem 1.1]) together with Theorem 1.1 suggested that fake linear cycles can be obtained as joins of 0-dimensional fake linear cycles inside hypersurfaces of $\mathbb{P}^1$, although the notion of fake cycle (defined in terms of the codimension of the tangent space of the Hodge locus) does not make sense in dimension 0. After finding the tensor decomposition structure described in Theorem 1.1 it became apparent that the appropriate notion of fake version of any $\frac{n}{2}$-dimensional algebraic subvariety of any n-dimensional smooth hypersurface of $\mathbb{P}^{n+1}$ for $n \geq 0$ (see Definition 7.1) should depend on the Hilbert function associated to a Hodge cycle (see Definition 6.1) and not only at its value at d. Using this new notion and the join construction we are able to show the following result which contradicts Movasati's conjecture in a major way for all degrees and dimensions.

Theorem 1.2. For any degree d and even dimension n, there are infinitely many smooth degree d hypersurfaces X of dimension n in $\mathbb{P}^{n+1}$ containing infinitely many $\frac{n}{2}$-dimensional fake linear cycles in $\mathbb{P}(H^{\frac{n}{2},\frac{n}{2}}(X, \mathbb{Q})_{\text{prim}})$.

Note that by Otwinowska's result, for $d >> n$ the Hodge loci of all fake linear cycles must have codimension strictly bigger than $\binom{\frac{n}{2}+d}{d} - (\frac{n}{2}+1)^2$, hence they are not smooth. Using Theorem 4.1 we show in fact that the Hodge loci of all fake linear cycles mentioned above are not smooth for $d \geq 2 + \frac{6}{n}$ (see Theorem 7.2). The main idea behind the proof of Theorem 1.2 is to construct fake linear cycles as joins of 0-dimensional fake linear cycles inside hypersurfaces of $\mathbb{P}^1$ with all their closed points defined over $\mathbb{Q}$. In this way we reduce ourselves to show the existence of fake linear cycles only at those 0-dimensional hypersurfaces.

The article is organized as follows: in Section 2 we recall some preliminaries about Artinian Gorenstein ideals and the quadratic fundamental form of a Hodge locus. Section 3 is devoted to the proof of Theorem 3.1 which is equivalent to Theorem 1.1. In Section 4 we deduce Theorem 1.1 and Theorem 4.1 which allows us to relate the quadratic fundamental form of the Hodge loci of two algebraic cycles and their join. Section 5 we illustrate in some concrete examples some uses of Theorem 4.1 by computing the Artinian Gorenstein ideal and their associated quadratic fundamental form for all combinations of two linear cycles inside Fermat varieties which are not known to have reduced Hodge loci. In Section 6 we introduce the Hilbert function associated to a Hodge cycle, and use this notion in Section 7 to introduce the concept of fake algebraic cycles. This section also contains the proof of Theorem 1.2.

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2 Preliminaries

2.1 Artinian Gorenstein ideal associated to a Hodge cycle

For the sake of completeness we will briefly recall some known facts about Artinian Gorenstein ideals associated to Hodge cycles in smooth hypersurfaces of the projective space. For a more complete exposition see [17].

Definition 2.1. A graded $\mathbb{C}$-algebra R is *Artinian Gorenstein* if there exist $\sigma \in \mathbb{N}$ such that

(i) $R_e = 0$ for all $e > \sigma$,

(ii) $\dim_{\mathbb{C}} R_\sigma = 1$,

(iii) the multiplication map $R_i \times R_{\sigma-i} \to R_\sigma$ is a perfect pairing for all $i = 0, \dots, \sigma$.

The number $\sigma =: \mathrm{soc}(R)$ is the *socle of* R. We say that an ideal $I \subseteq \mathbb{C}[x_0, \dots, x_{n+1}]$ is *Artinian Gorenstein of socle* $\sigma =: \mathrm{soc}(I)$ if the quotient ring $R = \mathbb{C}[x_0, \dots, x_{n+1}]/I$ is Artinian Gorenstein of socle σ.

The definition of the following ideal appeared first in the work of Voisin [20] for surfaces, and later in the work of Otwinowska [14] for higher dimensional varieties.

Definition 2.2. Let $X = \{F = 0\} \subseteq \mathbb{P}^{n+1}$ be a smooth degree d hypersurface of even dimension n, and $\lambda \in H^{\frac{n}{2},\frac{n}{2}}(X, \mathbb{Z})$ be a non-trivial Hodge cycle. Consider $J^F := \langle \frac{\partial F}{\partial x_0}, \dots, \frac{\partial F}{\partial x_{n+1}} \rangle$ to be the Jacobian ideal, we define the *Artinian Gorenstein ideal associated to* λ as

$$J^{F,\lambda} := (J^F : P_\lambda), \tag{5}$$

where $P_\lambda \in \mathbb{C}[x_0, \dots, x_{n+1}]_{(d-2)(\frac{n}{2}+1)}$ is such that $\lambda_{\mathrm{prim}} = \mathrm{res}\left(\frac{P_\lambda \Omega}{F^{\frac{n}{2}+1}}\right)^{\frac{n}{2},\frac{n}{2}}$. This ideal is Artinian Gorenstein of $\mathrm{soc}(J^{F,\lambda}) = (d-2)(\frac{n}{2}+1) = \frac{1}{2}\mathrm{soc}(J^F)$. We denote by $R^{F,\lambda} := \mathbb{C}[x_0, \dots, x_{n+1}]/J^{F,\lambda}$ its corresponding Artinian Gorenstein algebra.

Remark 2.1. The importance of this ideal is that it determines the cycle and its Hodge locus, that is (see for instance [17, Corollary 2.3, Remark 2.3])

$$J^{F,\lambda_1} = J^{F,\lambda_2} \iff \exists c \in \mathbb{Q}^\times : (\lambda_1 - c \cdot \lambda_2)_{\mathrm{prim}} = 0 \iff V_{\lambda_1} = V_{\lambda_2}.$$

This ideal also encodes the information of the first-order approximation of the Hodge loci in a simple way. More precisely, let $T \subseteq \mathbb{C}[x_0, \ldots, x_{n+1}]_d$ be the parameter space of smooth degree d hypersurfaces of $\mathbb{P}^{n+1}$, of even dimension n. For $t \in T$, let $X_t = \{F = 0\} \subseteq \mathbb{P}^{n+1}$ be the corresponding hypersurface. For every Hodge cycle $\lambda \in H^{\frac{n}{2},\frac{n}{2}}(X_t, \mathbb{Z})$, we can compute the Zariski tangent space of its associated Hodge locus V_λ as

$$T_t V_\lambda = J_d^{F,\lambda}. \tag{6}$$

Where we have identified $T_t T \simeq \mathbb{C}[x_0, \ldots, x_{n+1}]_d$.

2.2 Quadratic fundamental form

In this section we will explore the second order invariant of the IVHS associated to the Hodge locus $V_{[Z]}$ described by Maclean [7]. This invariant allows us to derive geometric information about the Hodge locus, namely the Hodge locus is either singular or non-reduced. For this type of application see [2].

The quadratic fundamental form was described in the context of surfaces for the classical Noether-Lefschetz loci by Maclean [7]. However in higher dimensions it also gives a partial description of the quadratic fundamental form.

Definition 2.3. Let M be a smooth m-dimensional analytic scheme, V a vector bundle on M and σ a section of V. Let W be the zero locus of σ and let $x \in W$. The *quadratic fundamental form of σ at x* is

$$q_{\sigma,x} : T_x W \otimes T_x W \to V_x/\mathrm{Im}(d\sigma_x)$$

given in local coordinates $(z_1, \ldots, z_m)$ around x by

$$q_{\sigma,x}\left(\sum_{i=1}^m \alpha_i \frac{\partial}{\partial z_i}, \sum_{j=1}^m \beta_j \frac{\partial}{\partial z_j}\right) = \sum_{i=1}^m \alpha_i \frac{\partial}{\partial z_i}\left(\sum_{j=1}^m \beta_j \frac{\partial}{\partial z_j}(\sigma)\right).$$

Remark 2.2. The quadratic fundamental form detects the second order approximation to W at x. In particular if W is smooth at x, then $q_{\sigma,x}$ vanishes.

In our context we will take $M = (T, 0)$, $V = \bigoplus_{p=0}^{\frac{n}{2}-1} \mathcal{F}^p/\mathcal{F}^{p+1}$ and $x = 0$. Where $T \subseteq H^0(\mathcal{O}_{\mathbb{P}^{n+1}}(d))$ is the parameter space of smooth degree d hypersurfaces of $\mathbb{P}^{n+1}$, $\pi : X \to T$ is the corresponding family, $\mathcal{F}^p = R^n\pi_*\Omega^{\bullet \geq p}_{X/T}$, and $0 \in T$ corresponds to the Fermat variety. In order to construct a section σ of V around x, let $\lambda \in H^{\frac{n}{2},\frac{n}{2}}(X_d^n)_{\mathrm{prim}} \cap H^n(X_d^n, \mathbb{Z})$ be a Hodge cycle, and consider $\overline{\lambda}$ its induced flat section in $\mathcal{F}^0/\mathcal{F}^{\frac{n}{2}}$. If we fix a holomorphic splitting $\mathcal{F}^0/\mathcal{F}^{\frac{n}{2}} \simeq V$ and we take σ as the image of $\overline{\lambda}$ under this splitting, then $W = V_\lambda$. In this context we can identify $T_x W = J_d^{F,\lambda}$ (6), $V_x = \bigoplus_{q=\frac{n}{2}+1}^n R^F_{d(q+1)-n-2}$ and $d\sigma_x = \cdot P_\lambda$. The computation of the degree $d + (d-2)(\frac{n}{2}+1)$ piece of $q = q_{\sigma,x}$ under these identifications was done by Maclean [7, Theorem 7] as follows.

Theorem 2.1 (Maclean)**.** The degree $r := d + (d-2)(\frac{n}{2}+1)$ piece of the fundamental quadratic form is $q|_{\mathrm{Sym}^2(J_d^{F,\lambda})}$ where

$$q : \mathrm{Sym}^2(J^{F,\lambda}) \to R^F/\langle P_\lambda \rangle$$

is the bilinear form given by

$$q(G,H)=\sum_{i=0}^{n+1}\left(H\frac{\partial Q_i}{\partial x_i}-R_i\frac{\partial G}{\partial x_i}\right) \tag{7}$$

where

$$G\cdot P_\lambda=\sum_{i=0}^{n+1}Q_i\frac{\partial F}{\partial x_i}\quad\text{and}\quad H\cdot P_\lambda=\sum_{i=0}^{n+1}R_i\frac{\partial F}{\partial x_i}.$$

Remark 2.3. In particular $q(\cdot,H)=0$ for any $H\in J^F$.

3 Periods of join of algebraic cycles

In this section we compute the periods of joins of algebraic cycles. Then we use this information to relate the cycle class and Artinian Gorenstein ideals of them. Let us recall the context we are working in.

We start with $\mathbb{P}^{n+1}$ odd dimensional (i.e. n even), and two odd dimensional (i.e. k is also even) linear subspaces $\mathbb{P}^{k+1},\mathbb{P}^{n-k-1}\subseteq\mathbb{P}^{n+1}$ such that $\mathbb{P}^{k+1}\cap\mathbb{P}^{n-k-1}=\varnothing$. Inside them we have the smooth degree d hypersurfaces $X_1:=\{f(x)=0\}\subseteq\mathbb{P}^{k+1}$, $X_2:=\{g(y)=0\}\subseteq\mathbb{P}^{n-k-1}$ and

$$X:=\{f(x)+g(y)=0\}\subseteq\mathbb{P}^{n+1}.$$

Each hypersurface contains a half dimensional algebraic cycle $Z_1\in\mathrm{CH}^{\frac{k}{2}}(X_1)$, $Z_2\in\mathrm{CH}^{\frac{n-k-2}{2}}(X_2)$ and their join $J(Z_1,Z_2)\in\mathrm{CH}^{\frac{n}{2}}(X)$.

Theorem 3.1. For any homogeneous polynomials $P(x)\in\mathbb{C}[x]$ and $Q(y)\in\mathbb{C}[y]$ such that $\deg(P(x)\cdot Q(y))=(d-2)(\frac{n}{2}+1)$ we have

$$\frac{\frac{n}{2}!}{\frac{k}{2}!\cdot\frac{n-k-2}{2}!}\int_{J(Z_1,Z_2)}\mathrm{res}\left(\frac{P(x)Q(y)\Omega}{(f(x)+g(y))^{\frac{n}{2}+1}}\right)=-2\pi i\cdot\int_{Z_1}\mathrm{res}\left(\frac{P\Omega'}{f^{\frac{k}{2}+1}}\right)\cdot\int_{Z_2}\mathrm{res}\left(\frac{Q\Omega''}{g^{\frac{n-k}{2}}}\right) \tag{8}$$

if $\deg(P)=(d-2)(\frac{k}{2}+1)$ and $\deg(Q)=(d-2)(\frac{n-k}{2})$, and is zero otherwise. Where Ω, Ω', and Ω'' are the standard top forms of $\mathbb{P}^{n+1}$, $\mathbb{P}^{k+1}$ and $\mathbb{P}^{n-k-1}$ respectively.

Proof In order to avoid confusion let $u=(u_0:\cdots:u_{k+1})$ be the coordinates of $\mathbb{P}^{k+1}$, $v=(v_0:\cdots:v_{n-k-1})$ be the coordinates of $\mathbb{P}^{n-k-1}$ and $(x:y)=(x_0:\cdots:x_{k+1}:y_0:\cdots:y_{n-k-1})$ be the coordinates of $\mathbb{P}^{n+1}$. Since (8) is independent of the choice of coordinates for $\mathbb{P}^{k+1}$ and $\mathbb{P}^{n-k-1}$, we can assume by Bertini's theorem that $X_1\cap\{u_0=0\}$ and $X_2\cap\{v_0=0\}$ are smooth hyperplane sections. By the bilinearity of (8) we can reduce ourselves to the case of monomials $P(x)=x^\alpha$ and $Q(y)=y^\beta$. Let us treat first the case where $\deg(x^\alpha)=(d-2)(\frac{k}{2}+1)$ and $\deg(y^\beta)=(d-2)(\frac{n-k}{2})$. Let us denote

$$\omega_{\alpha\beta}:=\mathrm{res}\left(\frac{x^\alpha y^\beta\Omega}{(f(x)+g(y))^{\frac{n}{2}+1}}\right)^{\frac{n}{2},\frac{n}{2}}\in H^{\frac{n}{2}}(X,\Omega_X^{\frac{n}{2}}),$$

$$\omega_\alpha := \operatorname{res}\left(\frac{u^\alpha \Omega'}{f(u)^{\frac{k}{2}+1}}\right)^{\frac{k}{2},\frac{k}{2}} \in H^{\frac{k}{2}}(X_1, \Omega_{X_1}^{\frac{k}{2}}),$$

$$\omega_\beta := \operatorname{res}\left(\frac{v^\beta \Omega''}{g(v)^{\frac{n-k}{2}}}\right)^{\frac{n-k-2}{2},\frac{n-k-2}{2}} \in H^{\frac{n-k-2}{2}}(X_2, \Omega_{X_2}^{\frac{n-k-2}{2}}).$$

Consider the birational map

$$\varphi : \mathbb{P}^{k+1} \times \mathbb{P}^{n-k-1} \times \mathbb{P}^1 \dashrightarrow \mathbb{P}^{n+1}$$

$$\varphi(u, v, t) = (t_0 v_0 u : t_1 u_0 v)$$

whose indeterminacy locus is given by $C_0 \cup C_1 \cup C_2$ for

$$C_0 = \{u_0 = v_0 = 0\}, \quad C_1 = \{u_0 = t_0 = 0\}, \quad C_2 = \{v_0 = t_1 = 0\}.$$

Let $\mathbb{P}_\Sigma$ be the projective simplicial toric variety obtained by successively blowing-up C_0, C_1 and C_2

$$\begin{tikzcd} \mathbb{P}_\Sigma \arrow[r, "\pi"] \arrow[dr, "\widetilde{\varphi}"'] & \mathbb{P}^{k+1} \times \mathbb{P}^{n-k-1} \times \mathbb{P}^1 \arrow[d, dashed, "\varphi"] \\ & \mathbb{P}^{n+1} \end{tikzcd} .$$

Let us denote their Cox rings by

$$\begin{aligned} S(\mathbb{P}^{n+1}) &= \mathbb{C}[x_0, \dots, x_{k+1}, y_0, \dots, y_{n-k-1}], \\ S(\mathbb{P}^{k+1} \times \mathbb{P}^{n-k-1} \times \mathbb{P}^1) &= \mathbb{C}[u_0, \dots, u_{k+1}, v_0, \dots, v_{n-k-1}, t_0, t_1], \\ S(\mathbb{P}_\Sigma) &= \mathbb{C}[a_0, \dots, a_{k+1}, b_0, \dots, b_{n-k-1}, s_0, s_1, e_0, e_1, e_2], \end{aligned}$$

hence we have the identifications induced by φ and π

$$\begin{aligned} x_0 = t_0 u_0 v_0, \ \dots \ , \quad x_{k+1} &= t_0 u_{k+1} v_0, \\ y_0 = t_1 u_0 v_0, \ \dots \ , \ y_{n-k-1} &= t_1 u_0 v_{n-k-1}, \\ u_0 = a_0 e_0 e_1, \ u_1 = a_1, \ \dots \ , \quad u_{k+1} &= a_{k+1}, \\ v_0 = b_0 e_0 e_2, \ \ v_1 = b_1, \ \dots \ , v_{n-k-1} &= b_{n-k-1}, \\ t_0 = s_0 e_1, \ t_1 &= s_1 e_2. \end{aligned}$$

In order to understand the fan of $\mathbb{P}_\Sigma$ let us write first the primitive generators of the rays corresponding to each variable. Let M_1, M_2 and M_3 be the character lattices of $\mathbb{P}^{k+1}$, $\mathbb{P}^{n-k-1}$ and $\mathbb{P}^1$ respectively. Let $N_i := M_i^\vee$ be the dual lattice. Then, the primitive generators of the rays of Σ belong to $N := N_1 \oplus N_2 \oplus N_3$. Let us denote by $\{r_j^{(i)}\}_j$ the canonical basis of N_i, then the primitive generators of the rays of $\Sigma(1)$ correspond to

$$\rho_{a_i} = (r_i^{(1)}, 0, 0), \quad \rho_{a_0} = -\sum_{i=1}^{k+1} \rho_{a_i}, \quad \rho_{b_j} = (0, r_j^{(2)}, 0), \quad \rho_{b_0} = -\sum_{j=1}^{n-k-1} \rho_{b_j},$$

$$\rho_{s_1} = (0, 0, r_1^{(3)}), \quad \rho_{s_0} = -\rho_{s_1}, \quad \rho_{e_0} = \rho_{a_0} + \rho_{b_0}, \quad \rho_{e_1} = \rho_{a_0} + \rho_{s_0}, \quad \rho_{e_2} = \rho_{b_0} + \rho_{s_1},$$

for $i=1,\dots,k+1$ and $j=1,\dots,n-k-1$. In order to describe the (maximal) cones of $\Sigma(n+1)$, we write the generators of its irrelevant ideal as follows

$$\begin{aligned}B(\Sigma)=\Big\langle\big\{&a_0a_ib_0b_js_0e_1,\ a_0a_ib_js_0s_1e_1,\ a_0a_ib_js_1e_1e_2,\ a_ib_0b_js_0e_1e_2,\ a_0a_ib_0b_js_1e_2,\\ &a_ib_0b_js_0s_1e_2,\ a_0b_0b_js_0e_0e_1,\ a_0b_js_0s_1e_0e_1,\ a_0b_js_1e_0e_1e_2,\ a_ib_0s_0e_0e_1e_2,\\ &a_0a_ib_0s_1e_0e_2,\ a_ib_0s_0s_1e_0e_2,\ a_0b_0s_0e_0e_1e_2,\ a_0b_0s_1e_0e_1e_2\big\}_{\substack{1\le\ i\ \le\ k+1\\ 1\le\ j\ \le\ n-k-1}}\Big\rangle.\end{aligned}$$

Let $Y\subseteq\mathbb{P}_\Sigma$ be the strict transform of $X\subseteq\mathbb{P}^{n+1}$ under the birational morphism $\widetilde{\varphi}$. In particular

$$Y=\{F:=(s_0b_0)^df(u)+(s_1a_0)^dg(v)=0\}\subseteq\mathbb{P}_\Sigma$$

is a smooth hypersurface (here we use that $X_1\cap\{u_0=0\}$ and $X_2\cap\{v_0=0\}$ are smooth). Let $W\in\mathrm{CH}^{\frac{n}{2}}(Y)$ be the strict transform of $J(Z_1,Z_2)\in\mathrm{CH}^{\frac{n}{2}}(X)$. Since $\pi_*(W)=Z_1\times Z_2\times\mathbb{P}^1$, in order to obtain (8) it is enough to check that

$$\frac{\frac{n}{2}!}{\frac{k}{2}!\cdot\frac{n-k-2}{2}!}\cdot\int_W\widetilde{\varphi}^*\omega_{\alpha\beta}=-\int_W\pi^*(\mathrm{pr}_1^*\omega_\alpha\cup\mathrm{pr}_2^*\omega_\beta\cup\mathrm{pr}_3^*\theta)\tag{9}$$

for $\theta\in H^1(\mathbb{P}^1,\Omega^1_{\mathbb{P}^1})$ the polarization (whose period is $2\pi i$). Let

$$X_{1,2}:=\{f(x)=g(y)=0\}\subseteq X\subseteq\mathbb{P}^{n+1}$$

which is a smooth complete intersection of bi-degree (d,d), and $J(Z_1,Z_2)\in\mathrm{CH}^{\frac{n}{2}}(X_{1,2})$. Since the open sets $V_j:=\{x_j\frac{\partial f(x)}{\partial x_j}\neq0\}$ and $V'_\ell:=\{y_\ell\frac{\partial g(y)}{\partial y_\ell}\neq0\}$ cover $X_{1,2}$ for $j=0,\dots,k$ and $\ell=0,\dots,n-k-2$, we can assume by the moving lemma that $J(Z_1,Z_2)$ is supported in a collection of smooth subvarieties of $X_{1,2}$ contained in $\bigcup_{j=0}^{\frac{k}{2}}U_j\cup\bigcup_{\ell=0}^{\frac{n-k-2}{2}}V_\ell$. Let us denote by $W_0\subseteq Y$ the strict transform of any of such subvarieties. Thus, in order to prove (9) it is enough to show that

$$\frac{\frac{n}{2}!}{\frac{k}{2}!\cdot\frac{n-k-2}{2}!}\cdot\widetilde{\varphi}^*\omega_{\alpha\beta}|_{W_0}=-\pi^*(\mathrm{pr}_1^*\omega_\alpha\cup\mathrm{pr}_2^*\omega_\beta\cup\mathrm{pr}_3^*\theta)|_{W_0}\tag{10}$$

in $H^n_{\mathrm{dR}}(W_0,\mathbb{C})\simeq H^{\frac{n}{2}}(W_0,\Omega^{\frac{n}{2}}_{W_0})$. We can compute the left hand side of (10) using a toric version of a theorem due to Carlson and Griffiths [18, Theorem 8.1] which computes the residue map in Cech cohomology relative to the Jacobian cover $\mathcal{U}=\{U_i\}_{i=0}^{n+6}$ of Y, where $U_i=\{F_i\neq0\}$ and F_i are the partial derivatives of F with respect to the homogeneous coordinates of $\mathbb{P}_\Sigma$. Let us denote by Ω''' the standard top form of $\mathbb{P}_\Sigma$. Since $\widetilde{\varphi}^*\Omega=-e_0e_1e_2u_0^{n-k}v_0^{k+2}t_0^{k+1}t_1^{n-k-1}\Omega'''$, we get

$$\begin{aligned}\widetilde{\varphi}^*\omega_{\alpha\beta}&=\mathrm{res}\left(\frac{(t_0v_0)^{(d-2)(\frac{k}{2}+1)}(t_1u_0)^{(d-2)(\frac{n-k}{2})}u^\alpha v^\beta\widetilde{\varphi}^*\Omega}{(e_0e_1e_2)^{n+2}F^{\frac{n}{2}+1}}\right)^{\frac{n}{2},\frac{n}{2}}\\ &=-\mathrm{res}\left(\frac{s_0^{d(\frac{k}{2}+1)-1}s_1^{d(\frac{n-k}{2})-1}a_0^{d(\frac{n-k}{2})}b_0^{d(\frac{k}{2}+1)}e_0u^\alpha v^\beta\Omega'''}{F^{\frac{n}{2}+1}}\right)^{\frac{n}{2},\frac{n}{2}}\\ &=\frac{-1}{\frac{n}{2}!}\left\{\frac{s_0^{d(\frac{k}{2}+1)-1}s_1^{d(\frac{n-k}{2})-1}a_0^{d(\frac{n-k}{2})}b_0^{d(\frac{k}{2}+1)}e_0u^\alpha v^\beta\Omega'''_J}{F_J}\right\}_{|J|=\frac{n}{2}+1}\in H^{\frac{n}{2}}(\mathcal{U},\Omega_Y^{\frac{n}{2}}),\end{aligned}\tag{11}$$

where we are using the notation from [18]. On the other hand we have

$$\pi^*\mathrm{pr}_1^*\omega_\alpha|_{W_0} = \frac{1}{\frac{k}{2}!}\left\{\frac{u^\alpha\Omega'_K}{f_K}\right\}_{|K|=\frac{k}{2}+1} \in H^{\frac{k}{2}}(\pi^{-1}\mathrm{pr}_1^{-1}\mathcal{U}_1, \Omega^{\frac{k}{2}}_{W_0}),$$

$$\pi^*\mathrm{pr}_2^*\omega_\beta|_{W_0} = \frac{1}{\frac{n-k-2}{2}!}\left\{\frac{v^\beta\Omega''_L}{g_L}\right\}_{|L|=\frac{n-k}{2}} \in H^{\frac{n-k-2}{2}}(\pi^{-1}\mathrm{pr}_2^{-1}\mathcal{U}_2, \Omega^{\frac{n-k-2}{2}}_{W_0}),$$

$$\pi^*\mathrm{pr}_3^*\theta|_{W_0} = \frac{t_0dt_1 - t_1dt_0}{t_0t_1} \in H^1(\pi^{-1}\mathrm{pr}_3^{-1}\mathcal{U}_3, \Omega^1_{W_0}),$$

where $\mathcal{U}_1$ and $\mathcal{U}_2$ are the Jacobian covers of X_1 and X_2 respectively, while $\mathcal{U}_3$ is the standard open cover of $\mathbb{P}^1$. When restricted to W_0, the coverings $\pi^{-1}\mathrm{pr}_1^{-1}\mathcal{U}_1$, $\pi^{-1}\mathrm{pr}_2^{-1}\mathcal{U}_2$ and $\pi^{-1}\mathrm{pr}_3^{-1}\mathcal{U}_3$ admit a common refinement $\mathcal{V} = \{V_{(j,\ell,r)}\}_{(j,\ell,r)} = \{V_{(j,0,0)}\}_{j=0}^{\frac{k}{2}} \cup \{V_{(0,\ell,1)}\}_{\ell=0}^{\frac{n-k-2}{2}}$ where

$$V_{(j,0,0)} = \{u_jf_j(u)v_0t_0 \neq 0\} = \widetilde{\varphi}^{-1}V_j \quad \text{and} \quad V_{(0,\ell,1)} = \{u_0v_\ell g_\ell(v)t_1 \neq 0\} = \widetilde{\varphi}^{-1}V'_\ell.$$

Hence

$$\frac{k}{2}!\cdot\frac{n-k-2}{2}!\cdot(\pi^*\mathrm{pr}_1^*\omega_\alpha|_{W_0} \cup \pi^*\mathrm{pr}_2^*\omega_\beta|_{W_0} \cup \pi^*\mathrm{pr}_3^*\theta|_{W_0})_{(j_1,\ell_1,r_1),\dots,(j_{\frac{n}{2}+1},\ell_{\frac{n}{2}+1},r_{\frac{n}{2}+1})} =$$

$$(-1)^{\frac{nk}{4}+\frac{n}{2}+1}\cdot\frac{u^\alpha v^\beta\Omega'_{(j_1,\dots,j_{\frac{k}{2}+1})}\wedge\Omega''_{(\ell_{\frac{k}{2}+1},\dots,\ell_{\frac{n}{2}})}\wedge(t_{r_{\frac{n}{2}}}dt_{r_{\frac{n}{2}+1}} - t_{r_{\frac{n}{2}+1}}dt_{r_{\frac{n}{2}}})}{f_{(j_1,\dots,j_{\frac{k}{2}+1})}(u)g_{(\ell_{\frac{k}{2}+1},\dots,\ell_{\frac{n}{2}})}(v)t_{r_{\frac{n}{2}}}t_{r_{\frac{n}{2}+1}}}$$

in Cech cohomology relative to the cover $\mathcal{V}$. We remark that the above formula for the cup product in Cech cohomology is well defined only for ordered tuples of indexes (the other tuples are defined by skew-symmetric extension), and the cohomology class is independent of this choice of the ordering. We will order the tuples (j,ℓ,r) lexicographically but with decreasing order in each entry. Then for an ordered set of tuples

$$\frac{k}{2}!\cdot\frac{n-k-2}{2}!\cdot(\pi^*(\mathrm{pr}_1^*\omega_\alpha \cup \mathrm{pr}_2^*\omega_\beta \cup \mathrm{pr}_3^*\theta)|_{W_0})_{(j_1,\ell_1,r_1),\dots,(j_{\frac{n}{2}+1},\ell_{\frac{n}{2}+1},r_{\frac{n}{2}+1})} = \tag{12}$$

$$(-1)^{\frac{nk}{4}+\frac{n}{2}+1}\cdot\frac{u^\alpha v^\beta\pi^*(\Omega'_{(\frac{k}{2},\dots,0)})\wedge\pi^*(\Omega''_{(\frac{n-k-2}{2},\dots,0)})\wedge(s_1e_2d(s_0e_1)-s_0e_1d(s_1e_2))}{f_{(0,\dots,\frac{k}{2})}(u)g_{(0,\dots,\frac{n-k-2}{2})}(v)s_0s_1e_1e_2}$$

if $(j_1,\dots,j_{\frac{k}{2}+1}) = (\frac{k}{2},\dots,0)$, $(\ell_{\frac{k}{2}+1},\dots,\ell_{\frac{n}{2}}) = (\frac{n-k-2}{2},\dots,0)$ and $(r_{\frac{n}{2}}, r_{\frac{n}{2}+1}) = (1,0)$, and is zero otherwise. Now it is routine to verify (10) in the open covering $\mathcal{V}$ (which is a sub-covering of $\mathcal{U}|_{W_0}$) using (11) and (12).

For the case where $\deg(x^\alpha) \neq (d-2)(\frac{k}{2}+1)$, let $r := \deg(x^\alpha) - (d-2)(\frac{k}{2}+1)$. By the same argument as above, it is enough for us to show that

$$\widetilde{\varphi}^*\omega_{\alpha\beta}|_{W_0} = 0 \in H^{\frac{n}{2}}(\mathcal{V}, \Omega^{\frac{n}{2}}_{W_0}).$$

Using (11) in this covering we can write

$$\widetilde{\varphi}^*\omega_{\alpha\beta}|_{W_0} = \pi^*(\mathrm{pr}_{12}^*\eta \cup \mathrm{pr}_3^*\widetilde{\theta})|_{W_0},$$

for $\eta \in H^{\frac{n}{2}-1}(\mathrm{pr}_{12}(\mathcal{V}), \Omega^{\frac{n}{2}-1}_{X_1\times X_2}|_{\mathrm{pr}_{12}(W_0)})$ given by

$$\eta_{(j_1,\ell_1,r_1),\dots,(j_{\frac{n}{2}},\ell_{\frac{n}{2}},r_{\frac{n}{2}})} = \left(\frac{v_0}{u_0}\right)^r \cdot \frac{u^\alpha v^\beta \Omega'_{(j_1,\dots,j_{\frac{k}{2}+1})} \wedge \Omega''_{(\ell_{\frac{k}{2}+1},\dots,\ell_{\frac{n}{2}})}}{f_{(j_1,\dots,j_{\frac{k}{2}+1})}(u) g_{(\ell_{\frac{k}{2}+1},\dots,\ell_{\frac{n}{2}})}(v)},$$

where each open set of the covering $\mathrm{pr}_{12}(\mathcal{V}) = \{T_{(j,\ell,r)}\} = \{T_{(j,0,0)}\}_{j=0}^{\frac{k}{2}} \cup \{T_{(0,\ell,1)}\}_{\ell=0}^{\frac{n-k-2}{2}}$ is of the form $T_{(j,0,0)} = \{u_j v_0 f_j(u) \neq 0\}$ or $T_{(0,\ell,1)} = \{u_0 v_\ell g_\ell(v) \neq 0\}$. And where

$$\widetilde{\theta} = \left(\frac{t_0}{t_1}\right)^r \theta \in H^1(\mathcal{U}_3, \Omega^1_{\mathbb{P}^1}).$$

The result follows since $\widetilde{\theta} = 0$ for $r \neq 0$. ■

4 Cycle class and Hodge loci of join algebraic cycles

In this section we translate the periods relation of Theorem 3.1 into relations of the corresponding cycle classes and Hodge loci in the context of join algebraic cycles. The first relation is the content of Theorem 1.1 which we prove in the following.

Proof of Theorem 1.1 Applying [16, Proposition 6.1] to Theorem 3.1 we obtain

$$c = \frac{\frac{n}{2}! \cdot d}{\frac{k}{2}! \cdot \frac{n-k-2}{2}!} c_1 c_2 \tag{13}$$

where $c, c_1, c_2 \in \mathbb{C}^\times$ are the unique complex numbers such that

$$\frac{(-1)^{\frac{n}{2}+1}\frac{n}{2}!}{d} PQP_{J(Z_1,Z_2)} \equiv c \cdot \det(\mathrm{Hess}(f+g)) \pmod{J^{f+g}}$$
$$\frac{(-1)^{\frac{k}{2}+1}\frac{k}{2}!}{d} PP_{Z_1} \equiv c_1 \cdot \det(\mathrm{Hess}(f)) \pmod{J^f}$$
$$\frac{(-1)^{\frac{n-k}{2}}\frac{n-k-2}{2}!}{d} QP_{Z_2} \equiv c_2 \cdot \det(\mathrm{Hess}(g)) \pmod{J^g}$$

for $P \in \mathbb{C}[x]_{(d-2)(\frac{k}{2}+1)}$ and $Q \in \mathbb{C}[y]_{(d-2)(\frac{n-k}{2})}$. Since $R^{f+g} = R^f \otimes R^g$ and $\det(\mathrm{Hess}(f+g)) = \det(\mathrm{Hess}(f)) \cdot \det(\mathrm{Hess}(g))$ it follows that

$$PQP_{J(Z_1,Z_2)} \equiv PQP_{Z_1}P_{Z_2} \pmod{J^{f+g}}$$

for all $P \in \mathbb{C}[x]_{(d-2)(\frac{k}{2}+1)}$ and $Q \in \mathbb{C}[y]_{(d-2)(\frac{n-k}{2})}$. In particular,

$$x^\alpha y^\beta (P_{J(Z_1,Z_2)} - P_{Z_1}P_{Z_2}) = 0 \in R^{f+g} \tag{14}$$

for all monomials such that $\deg(x^\alpha) = (d-2)(\frac{k}{2}+1)$ and $\deg(y^\beta) = (d-2)(\frac{n-k}{2})$. On the other hand if $\deg(x^\alpha) > (d-2)(\frac{k}{2}+1)$ then $x^\alpha P_{Z_1} = 0 \in R^{f+g}$ and similarly if $\deg(y^\beta) > (d-2)(\frac{n-k}{2})$

then $y^\beta P_{Z_2} = 0 \in R^{f+g}$. Hence, it follows from the second part of Theorem 3.1 that (14) holds for any monomial of degree $\deg(x^\alpha y^\beta) = (d-2)(\frac{n}{2}+1)$. Since R^{f+g} is Artinian Gorenstein of socle in degree $(d-2)(n+2)$ we obtain (2).

Now if an element $T \in R_e^{f+g}$ is zero in $R^{f+g,\delta} = R^{f,[Z_1]} \otimes R^{g,[Z_2]}$ then

$$T = \sum_{i=0}^{e} T_i(x) \cdot \check{T}_{e-i}(y)$$

where $T_i(x) \in R_i^f$, $\check{T}_{e-i}(y) \in R_{e-i}^g$ and for each $i = 0, \dots, e$, we have $T_i \in (J^f : P_{Z_1})$ or $\check{T}_{e-i} \in (J^g : P_{Z_2})$. Hence such a T satisfies that $T \cdot P_{Z_1} \cdot P_{Z_2} = 0 \in R^{f+g}$ and so

$$J^{f+g,\delta} \subseteq (J^{f+g}, P_{Z_1} \cdot P_{Z_2}) = J^{f+g,[J(Z_1,Z_2)]}.$$

Since both are Artinian Gorenstein ideals of socle in degree $(d-2)(\frac{n}{2}+1)$, they are equal and (3) follows from Remark 2.1. ∎

In Section 2.2 we recalled the quadratic fundamental form, which is a second order invariant of the Hodge loci that vanishes when the corresponding Hodge locus is smooth and reduced. As a consequence of Theorem 1.1 we can relate the quadratic fundamental form of $V_{[J(Z_1,Z_2)]}$ with those of $V_{[Z_1]}$ and $V_{[Z_2]}$ as follows.

Theorem 4.1. In the same context of Theorem 1.1 let us denote by

$$q : \mathrm{Sym}^2(J^{f+g,[J(Z_1,Z_2)]}) \to R^{f+g}/\langle P_{Z_1} \cdot P_{Z_2} \rangle,$$

$$q_1 : \mathrm{Sym}^2(J^{f,[Z_1]}) \to R^f/\langle P_{Z_1} \rangle,$$
$$q_2 : \mathrm{Sym}^2(J^{g,[Z_2]}) \to R^g/\langle P_{Z_2} \rangle,$$

the bilinear forms (introduced in Theorem 2.1) associated to $J(Z_1, Z_2)$, Z_1 and Z_2 respectively. Consider

$$G = A_1(x,y)G_1(x) + A_2(x,y)G_2(y) \in J^{f+g,[J(Z_1,Z_2)]}$$
$$H = B_1(x,y)H_1(x) + B_2(x,y)H_2(y) \in J^{f+g,[J(Z_1,Z_2)]}$$

with $G_1, H_1 \in J^{f,[Z_1]}$, $G_2, H_2 \in J^{g,[Z_2]}$. Then

$$q(G,H) = A_1 B_1 P_{Z_2} q_1(G_1, H_1) + A_2 B_2 P_{Z_1} q_2(G_2, H_2). \tag{15}$$

In consequence for any degree $e \geq 0$ we have the following:

(i) If q_1 and q_2 vanish in all degrees $\ell \leq e$, then q vanishes in degree e.

(ii) If q vanishes in degree e, then $q_1|_{\mathrm{Sym}^2(J_\ell^{f,[Z_1]})} \cdot \mathbb{C}[x]_j = 0 \in R^f/\langle P_{Z_1} \rangle$ for all degrees $\ell, j \geq 0$ such that $\ell \leq e$, $j \leq 2(e-\ell)$ and $2(e-\ell) - j \leq (d-2)(\frac{n-k}{2})$. One gets a similar assertion for q_2 by symmetry.

Proof Write

$$G_1 \cdot P_{Z_1} = \sum_{i=0}^{k+1} Q_i(x) \frac{\partial f}{\partial x_i} \quad , \quad G_2 \cdot P_{Z_2} = \sum_{j=0}^{n-k-1} R_j(y) \frac{\partial g}{\partial y_j} \ ,$$

$$H_1 \cdot P_{Z_1} = \sum_{i=0}^{k+1} S_i(x) \frac{\partial f}{\partial x_i} \quad , \quad H_2 \cdot P_{Z_2} = \sum_{j=0}^{n-k-1} T_j(y) \frac{\partial g}{\partial y_j} \ .$$

then it follows by (7) that

$$q(G,H) = A_1 B_1 P_{Z_2} q_1(G_1,H_1) + A_2 B_2 P_{Z_1} q_2(G_2,H_2)$$
$$+ B_1 P_{Z_2} \sum_{i=0}^{k+1} (H_1 Q_i - G_1 S_i) \frac{\partial A_1}{\partial x_i} + B_2 P_{Z_1} \sum_{j=0}^{n-k-1} (H_2 R_j - G_2 T_j) \frac{\partial A_2}{\partial y_j}.$$

Note that $\sum_{i=0}^{k+1} (H_1 Q_i - G_1 S_i) \frac{\partial f}{\partial x_i} = 0$ and $\sum_{j=0}^{n-k-1} (H_2 R_j - G_2 T_j) \frac{\partial g}{\partial y_j} = 0$. Since $(\frac{\partial f}{\partial x_0}, \dots, \frac{\partial f}{\partial x_{k+1}})$ and $(\frac{\partial g}{\partial y_0}, \dots, \frac{\partial g}{\partial y_{n-k-1}})$ are regular sequences, it follows by the exactness of the Koszul complex that $H_1 Q_i - G_1 S_i \in J^f$ and $H_2 R_j - G_2 T_j \in J^g$, and so we obtain (15). From (15) we obtain (i) by a direct computation in the generators of $J^{f+g,[J(Z_1,Z_2)]}$ which are generators of either $J^{f,[Z_1]}$ or $J^{g,[Z_2]}$ (by (3)).

In order to show (ii) consider $G = H = A(x,y) G_1(x)$ for any $\ell \leq e$ and any $G_1 \in J^{f,[Z_1]}_\ell$. Then by (15)

$$A^2 \cdot P_{Z_2} \cdot q_1(G_1,G_1) = 0 \in R^{f+g} / \langle P_{Z_1} \cdot P_{Z_2} \rangle$$

for all $A \in \mathbb{C}[x,y]_{e-\ell}$. In particular, for any monomial $x^\alpha y^\beta \in \mathbb{C}[x,y]_{2(e-\ell)}$ we can write it as $x^\alpha y^\beta = A_1 A_2$ with $A_1, A_2 \in \mathbb{C}[x,y]_{e-\ell}$ and so

$$x^\alpha y^\beta \cdot P_{Z_2} \cdot q_1(G_1,G_1) = \left(\frac{(A_1+A_2)^2}{4} - \frac{(A_1-A_2)^2}{4} \right) P_{Z_2} \cdot q_1(G_1,G_1) = 0 \in R^{f+g} / \langle P_{Z_1} \cdot P_{Z_2} \rangle.$$

From this, it follows in fact that for any $j \leq 2(e-\ell)$ and any two polynomials $Q(x) \in \mathbb{C}[x]_j$ and $S(y) \in \mathbb{C}[y]_{2(e-\ell)-j}$

$$Q \cdot S \cdot P_{Z_2} \cdot q_1(G_1,G_1) = 0 \in R^{f+g} / \langle P_{Z_1} \cdot P_{Z_2} \rangle.$$

As $2(e-\ell) - j \leq (d-2)(\frac{n-k}{2})$ we choose S such that $S \cdot P_{Z_2} \notin J^g$, then there exists some $T(x,y) \in \mathbb{C}[x,y]$ of bi-degree $(\ell + j, 2(e-\ell) - j)$ such that

$$P_{Z_2}(Q(x) \cdot S(y) \cdot q_1(G_1,G_1) - T(x,y) \cdot P_{Z_1}) \in J^{f+g}. \tag{16}$$

Considering $S_1(y), \dots, S_t(y) \in \mathbb{C}[y]_{2(e-\ell)-j}$ such that $\{S(y), S_1(y), \dots, S_t(y)\}$ is a basis of $R^g_{2(e-\ell)-j}$ and $\{S_1(y), \dots, S_p(y)\}$ is a basis of $\ker(R^g_{2(e-\ell)-j} \xrightarrow{\cdot P_{Z_2}} R^g_{2(e-\ell)+(d-2)(\frac{n-k}{2})-j})$ we can write

$$T(x,y) = U(x) S(y) + \sum_{h=1}^{t} U_h(x) S_h(y) \in R^{f+g}.$$

Since $\{P_{Z_2} S(y), P_{Z_2} S_{p+1}(y), \dots, P_{Z_2} S_t(y)\}$ is a basis of $R^g_{2(e-\ell)+(d-2)(\frac{n-k}{2})-j}$ and $R^{f+g} = R^f \otimes R^g$, then (16) is equivalent to have

$$Q(x) \cdot q_1(G_1,G_1) - U(x) \cdot P_{Z_1} = 0 \in R^f$$

and $P_{Z_1}U_h(x) = 0 \in R^f$ for all $h = p+1, \ldots, t$. Therefore $Q(x) \cdot q_1(G_1, G_1) = 0 \in R^f/\langle P_{Z_1}\rangle$ for all $Q(x) \in \mathbb{C}[x]_j$. ■

5 Examples in Fermat varieties

In this section we give examples of join algebraic cycles inside Fermat varieties, illustrating how we can use the join structure to simplify their study. We focus on combinations of two linear cycles inside low degrees Fermat varieties, whose corresponding Hodge locus is not known to be reduced. This kind of combinations have already been studied by Movasati, Kloosterman and the second author [5,10,10,12,16] as a non-trivial case to study the Variational Hodge Conjecture for reducible algebraic cycles.

Along this section $X := \{F := x_0^d + \cdots + x_{n+1}^d = 0\}$ is the degree d Fermat variety of even dimension n. Its automorphism group corresponds to $\mathrm{Aut}(X) = G \rtimes \mathfrak{S}_{n+2}$, where $\mathfrak{S}_{n+2}$ acts by permutation on the coordinates and $G = (\mathbb{Z}/d\mathbb{Z})^{n+2}/\mathrm{Im}(a \in \mathbb{Z}/d\mathbb{Z} \mapsto (a, \ldots, a) \in (\mathbb{Z}/d\mathbb{Z})^{n+2}) \simeq (\mathbb{Z}/d\mathbb{Z})^{n+1}$ acts diagonally as

$$g \cdot (x_0 : \cdots : x_{n+1}) = (\zeta_d^{g_0} x_0 : \cdots : \zeta_d^{g_{n+1}} x_{n+1}),$$

where for any $k > 0$, ζ_k denotes the k-th primitive root of unity $e^{\frac{2\pi i}{k}}$. The Fermat variety contains several $\frac{n}{2}$-dimensional linear cycles, which are obtained as the orbit under the action of $\mathrm{Aut}(X)$ on the cycle

$$\mathbb{P}^{\frac{n}{2}} := \{x_0 - \zeta_{2d}x_1 = x_2 - \zeta_{2d}x_3 = \cdots = x_n - \zeta_{2d}x_{n+1} = 0\}.$$

Example 5.1. Consider the zero dimensional Fermat variety $X_0 = \{x_0^d + x_1^d = 0\}$, and a point $Z_0 = \{(\zeta_{2d} : 1)\} \subseteq X_0$. Since this is a complete intersection cycle, it follows by [16, Theorem 1.1] that the cycle class of Z_0 has primitive part

$$[Z_0]_{\mathrm{prim}} = \frac{-1}{d}\mathrm{res}\left(\frac{P_{Z_0}(x_0dx_1 - x_1dx_0)}{x_0^d + x_1^d}\right)$$

for the associated degree $(d-2)$ polynomial

$$P_{Z_0} = d\zeta_{2d}\left(\frac{x_0^{d-1} - (\zeta_{2d}x_1)^{d-1}}{x_0 - \zeta_{2d}x_1}\right).$$

Consequently $J^{x_0^d+x_1^d,[Z_0]} = \langle x_0 - \zeta_{2d}x_1, x_1^{d-1}\rangle$ and the quadratic fundamental form q vanishes (by Remark 2.3 this is reduced to check that $q(x_0 - \zeta_{2d}x_1, x_0 - \zeta_{2d}x_1) = 0$).

For higher dimensions, the Fermat polynomial $x_0^d + \cdots + x_{n+1}^d$ can be written as a sum of $\frac{n}{2}+1$ Fermat polynomials in two variables. Let $X_i = \{x_{2i-2}^d + x_{2i-1}^d = 0\}$, and $Z_i = \{(\zeta_{2d} : 1)\} \subseteq X_i$ for each $i = 1, \ldots, \frac{n}{2}+1$, then

$$\mathbb{P}^{\frac{n}{2}} = J(Z_1, \ldots, Z_{\frac{n}{2}+1}).$$

In consequence

$$P_{\mathbb{P}^{\frac{n}{2}}} = d^{\frac{n}{2}+1}\zeta_{2d}^{\frac{n}{2}+1}\prod_{i=1}^{\frac{n}{2}+1}\left(\frac{x_{2i-2}^{d-1} - (\zeta_{2d}x_{2i-1})^{d-1}}{x_{2i-2} - \zeta_{2d}x_{2i-1}}\right)$$

and so $J^{F,[\mathbb{P}^{\frac{n}{2}}]} = \langle x_0 - \zeta_{2d}x_1, x_1^{d-1}, \dots, x_n - \zeta_{2d}x_{n+1}, x_{n+1}^{d-1}\rangle$. By item (i) of Theorem 4.1 its quadratic fundamental form also vanishes. One can do similar computations for all other linear cycles in the Fermat variety.

Example 5.2. Let $-1 \leq m \leq \frac{n}{2}$ be an integer. Consider inside $\mathbb{P}^{n+1}$ the linear subvarieties

$$\mathbb{P}^{n-m} := \{x_{n-2m} - \zeta_{2d}x_{n-2m+1} = x_{n-2m+2} - \zeta_{2d}x_{n-2m+3} = \cdots = x_n - \zeta_{2d}x_{n+1} = 0\},$$
$$\mathbb{P}^{\frac{n}{2}} := \{x_0 - \zeta_{2d}x_1 = x_2 - \zeta_{2d}x_3 = \cdots = x_{n-2m-2} - \zeta_{2d}x_{n-2m-1} = 0\} \cap \mathbb{P}^{n-m},$$
$$\check{\mathbb{P}}^{\frac{n}{2}} := \{x_0 - \zeta_{2d}^{\alpha_0}x_1 = \cdots = x_{n-2m-2} - \zeta_{2d}^{\alpha_{n-2m-2}}x_{n-2m-1} = 0\} \cap \mathbb{P}^{n-m},$$

where $\alpha_0, \alpha_2, \dots, \alpha_{n-2m-2} \in \{3, 5, \dots, 2d-1\}$. Then

$$\mathbb{P}^m := \mathbb{P}^{\frac{n}{2}} \cap \check{\mathbb{P}}^{\frac{n}{2}} = \{x_0 = x_1 = x_2 = x_3 = \cdots = x_{n-2m-1} = 0\} \cap \mathbb{P}^{n-m}.$$

It turns out that the linear combination $Z := r\mathbb{P}^{\frac{n}{2}} + \check{r}\check{\mathbb{P}}^{\frac{n}{2}}$ of these two $\frac{n}{2}$-dimensional linear cycles is a join algebraic cycle, for all $r, \check{r} \in \mathbb{Z} \setminus \{0\}$. In fact, inside each degree d Fermat variety

$$X_1 := \{f := x_0^d + \cdots + x_{n-2m-1}^d = 0\} \subseteq \mathbb{P}^{n-2m-1}$$

and

$$X_2 := \{g := x_{n-2m}^d + \cdots + x_{n+1}^d = 0\} \subseteq \mathbb{P}^{2m+1}$$

we can consider the algebraic cycles $Z_1 \in \mathrm{CH}^{\frac{n}{2}-m-1}(X_1)$ and $Z_2 \in \mathrm{CH}^m(X_2)$ given by

$$Z_1 := rL + \check{r}\check{L},$$
$$Z_2 := \{x_{n-2m} - \zeta_{2d}x_{n-2m+1} = x_{n-2m+2} - \zeta_{2d}x_{n-2m+3} = \cdots = x_n - \zeta_{2d}x_{n+1} = 0\} \subseteq X_2,$$

where

$$L := \{x_0 - \zeta_{2d}x_1 = x_2 - \zeta_{2d}x_3 = \cdots = x_{n-2m-2} - \zeta_{2d}x_{n-2m-1} = 0\} \subseteq X_1,$$
$$\check{L} := \{x_0 - \zeta_{2d}^{\alpha_0}x_1 = x_2 - \zeta_{2d}^{\alpha_2}x_3 = \cdots = x_{n-2m-2} - \zeta_{2d}^{\alpha_{n-2m-2}}x_{n-2m-1} = 0\} \subseteq X_1.$$

Since $\mathbb{P}^{\frac{n}{2}} = J(L, Z_2)$ and $\check{\mathbb{P}}^{\frac{n}{2}} = J(\check{L}, Z_2)$ then

$$Z = r\mathbb{P}^{\frac{n}{2}} + \check{r}\check{\mathbb{P}}^{\frac{n}{2}} = rJ(L, Z_2) + \check{r}J(\check{L}, Z_2) = J(Z_1, Z_2) \in \mathrm{CH}^{\frac{n}{2}}(X),$$

where $X = \{F := f + g = x_0^d + \cdots + x_{n+1}^d = 0\}$ is the n-dimensional Fermat variety. By [16, Theorem 1.3] the Hodge locus $V_{[Z]}$ satisfies

$$V_{[Z]} = V_{[\mathbb{P}^{\frac{n}{2}}]} \cap V_{[\check{\mathbb{P}}^{\frac{n}{2}}]}$$

whenever $d \geq 3$ and $m < \frac{n}{2} - \frac{d}{d-2}$. On the other hand, it follows from [9, Propositions 17.8 and 17.9] that $V_{[\mathbb{P}^{\frac{n}{2}}]} \cap V_{[\check{\mathbb{P}}^{\frac{n}{2}}]}$ is smooth and reduced without restrictions on d and m. In particular, for $d \geq 3$ and $m < \frac{n}{2} - \frac{d}{d-2}$, $V_{[Z]}$ is smooth and reduced. The cases not covered in [16, Theorem 1.3] are: $(d, m) = (3, \frac{n}{2} - 3)$, in which case Movasati conjectured $V_{[Z]}$ is smooth (see [10]), $(d, m) = (3, \frac{n}{2} - 2), (4, \frac{n}{2} - 2)$ and $m = \frac{n}{2} - 1$ with $r \neq \check{r}$. In this last case when $r = \check{r}$ the algebraic cycle Z is a complete intersection and $V_{[Z]}$ parametrizes hypersurfaces containing a complete intersection of type $(1, 1, \dots, 1, 2)$. In the recent article [5] Kloosterman showed that if $(d, m) = (3, \frac{n}{2} - 3)$, $n \geq 10$ and $r \neq \check{r}$ then $V_{[Z]}$ is not smooth, disproving Movasati's conjecture. Moreover, he showed that when $r = \check{r}$ and $n \geq 4$, $V_{[Z]}$ is smooth. Similar results are obtained by Kloosterman in the cases $(d, m) = (3, \frac{n}{2} - 2)$ and $(4, \frac{n}{2} - 2)$. We will analyze each of the above cases separately, using the join description to determine their associated Artin Gorenstein ideals and corresponding quadratic fundamental forms.

Proposition 5.1. Consider the notation of Example 5.2. For $d = 3$, $n \geq 4$, $m = \frac{n}{2} - 3$, the Artinian Gorenstein ideal $J^{F,[Z]}$ associated to the algebraic cycle Z is

$$\begin{aligned} J^{F,[Z]} =& \Big\langle \{x_j^2\}_{j=0}^{n+1},\ \{x_{2j} - \zeta_6 x_{2j+1}\}_{j=3}^{\frac{n}{2}},\ \{x_{2j}x_{2j+1}\}_{j=0}^{2},\ A_1x_1x_3x_4 + A_2x_1x_3x_5 \\ & x_0x_2 + B_1x_1x_2 + B_2x_1x_3,\ x_0x_3 + C_1x_1x_2 + C_2x_1x_3,\ x_0x_4 + D_1x_1x_4 + D_2x_1x_5 \\ & x_0x_5 + E_1x_1x_4 + E_2x_1x_5,\ x_2x_4 + F_1x_3x_4 + F_2x_3x_5,\ x_2x_5 + G_1x_3x_4 + G_2x_3x_5 \Big\rangle \end{aligned}$$

where $(A_1 : A_2) = (-r + \check{r}\zeta_6^{\alpha_0+\alpha_2+\alpha_4} : r\zeta_6 - \check{r}\zeta_6^{\alpha_0+\alpha_2+2\alpha_4}) \in \mathbb{P}^1$,

$$B_1 = \frac{-(\zeta_6^{\alpha_0+\alpha_2} - \zeta_6)}{\zeta_6^{\alpha_2} - \zeta_6},\ B_2 = \frac{\zeta_6^{\alpha_2+1}(\zeta_6^{\alpha_0} - \zeta_6)}{\zeta_6^{\alpha_2} - \zeta_6},\ C_1 = \frac{-(\zeta_6^{\alpha_0} - \zeta_6)}{\zeta_6^{\alpha_2} - \zeta_6},\ C_2 = \frac{\zeta_6(\zeta_6^{\alpha_0} - \zeta_6^{\alpha_2})}{\zeta_6^{\alpha_2} - \zeta_6},$$

$$D_1 = \frac{-(\zeta_6^{\alpha_0+\alpha_4} - \zeta_6^2)}{\zeta_6^{\alpha_4} - \zeta_6},\ D_2 = \frac{\zeta_6^{\alpha_4+1}(\zeta_6^{\alpha_0} - \zeta_6)}{\zeta_6^{\alpha_4} - \zeta_6},\ E_1 = \frac{-(\zeta_6^{\alpha_0} - \zeta_6)}{\zeta_6^{\alpha_4} - \zeta_6},\ E_2 = \frac{\zeta_6(\zeta_6^{\alpha_0} - \zeta_6^{\alpha_4})}{\zeta_6^{\alpha_4} - \zeta_6},$$

$$F_1 = \frac{-(\zeta_6^{\alpha_2+\alpha_4} - \zeta_6^2)}{\zeta_6^{\alpha_4} - \zeta_6},\ F_2 = \frac{\zeta_6^{\alpha_4+1}(\zeta_6^{\alpha_2} - \zeta_6)}{\zeta_6^{\alpha_4} - \zeta_6},\ G_1 = \frac{-(\zeta_6^{\alpha_2} - \zeta_6)}{\zeta_6^{\alpha_4} - \zeta_6},\ G_2 = \frac{\zeta_6(\zeta_6^{\alpha_2} - \zeta_6^{\alpha_4})}{\zeta_6^{\alpha_4} - \zeta_6}.$$

In particular, the degree $k := \frac{n}{2}+4$ piece of the quadratic fundamental form vanishes on $\mathrm{Sym}^2(J_3^{F,[Z]})$.

Proof Since $Z = J(Z_1, Z_2)$ is a join algebraic cycle, by Theorem 1.1 it is enough to compute $J^{f,[Z_1]}$ and $J^{g,[Z_2]}$. In Example 5.1 we already computed $J^{g,[Z_2]}$, and so we just need to show that

$$\begin{aligned} J^{f,[Z_1]} =& \Big\langle x_0^2,\ x_1^2,\ x_2^2,\ x_3^2,\ x_4^2,\ x_5^2,\ x_0x_1,\ x_2x_3,\ x_4x_5,\ A_1x_1x_3x_4 + A_2x_1x_3x_5 \\ & x_0x_2 + B_1x_1x_2 + B_2x_1x_3,\ x_0x_3 + C_1x_1x_2 + C_2x_1x_3,\ x_0x_4 + D_1x_1x_4 + D_2x_1x_5 \\ & x_0x_5 + E_1x_1x_4 + E_2x_1x_5,\ x_2x_4 + F_1x_3x_4 + F_2x_3x_5,\ x_2x_5 + G_1x_3x_4 + G_2x_3x_5 \Big\rangle. \end{aligned}$$

Note that the right hand side is contained in the left hand side. Assume that $A_1 \neq 0$ (the case where $A_1 = 0$ is analogue), then the ideal generated by the leading terms in the lexicographic monomial ordering is

$$\langle x_0^2, x_1^2, x_2^2, x_3^2, x_4^2, x_5^2, x_0x_1, x_0x_2, x_0x_3, x_0x_4, x_0x_5, x_2x_3, x_2x_4, x_2x_5, x_4x_5, x_1x_3x_4 \rangle \subseteq \mathrm{LT}(J^{f,[Z_1]}).$$

Thus if we show that both monomial ideals have the same Hilbert function we are done (and in fact we conclude that the generators given above are a Gröbner basis of $J^{f,[Z_1]}$). To see this, note that for the left hand side monomial ideal, it is very easy to compute its Hilbert function, and in fact we see that the quotient ring has Hilbert function 1, 6, 6, 1, and 0 for degree bigger than 3. On the other hand the Hilbert function of $R^{f,[Z_1]}$ is of the form 1, ℓ, ℓ, 1 and 0 for degree bigger than 3 (since J^{f,Z_1} is Artinian Gorenstein of socle in degree 3). Thus it is reduced to show that $\ell = 6$. In other words, to show that $J_1^{f,[Z_1]} = 0$. And this can be shown using [16, Proposition 2.1]. The last statement about the quadratic fundamental form follows from Theorem 4.1 item (i) and a routine verification that the quadratic fundamental form $q_1|_{\mathrm{Sym}^2(J^{f,[Z_1]})}$ vanishes in degree ≤ 3. ■

Proposition 5.2. In the context of Example 5.2 consider $d=3$, $n\geq 2$ and $m=\frac{n}{2}-2$. The Artinian Gorenstein ideal $J^{F,[Z]}$ associated to algebraic cycle Z is

$$J^{F,[Z]}=\Big\langle \{x_j^2\}_{j=0}^{2n+1},\ \{x_{2j}-\zeta_6x_{2j+1}\}_{j=2}^{\frac{n}{2}},\ x_0x_1,\ x_2x_3,\ A_1x_1x_2+A_2x_1x_3,$$
$$B_1x_0x_2+B_2x_1x_2+B_3x_1x_3,\ C_1x_0x_3+C_2x_1x_2+C_3x_1x_3\Big\rangle$$

where $(A_1:A_2)=(r\zeta_6^2+\check{r}\zeta_6^{\alpha_0+\alpha_2}:r-\check{r}\zeta_6^{\alpha_0+2\alpha_2})\in\mathbb{P}^1$,

$$(B_1:B_2:B_3)=\begin{cases}(r\zeta_6^2+\check{r}\zeta_6^{\alpha_0+\alpha_2}:0:r\zeta_6-\check{r}\zeta_6^{2(\alpha_0+\alpha_2)}) & \text{if } A_1\neq 0,\\ (r-\check{r}\zeta_6^{\alpha_0+2\alpha_2}:-r\zeta_6+\check{r}\zeta_6^{2(\alpha_0+\alpha_2)}:0) & \text{if } A_1=0,\end{cases}$$

$$(C_1:C_2:C_3)=\begin{cases}(r\zeta_6^2+\check{r}\zeta_6^{\alpha_0+\alpha_2}:0:r-\check{r}\zeta_6^{2\alpha_0+\alpha_2}) & \text{if } A_1\neq 0,\\ (r-\check{r}\zeta_6^{\alpha_0+2\alpha_2}:-r+\check{r}\zeta_6^{2\alpha_0+\alpha_2}:0) & \text{if } A_1=0.\end{cases}$$

In particular, the degree $k:=\frac{n}{2}+4$ piece of the quadratic fundamental form vanishes.

Proof As in the proof of the previous proposition we just need to show that

$$J^{f,[Z_1]}=\Big\langle x_0^2,\ x_1^2,\ x_2^2,\ x_3^2,\ x_0x_1,\ x_2x_3,\ A_1x_1x_2+A_2x_1x_3,$$
$$B_1x_0x_2+B_2x_1x_2+B_3x_1x_3,\ C_1x_0x_3+C_2x_1x_2+C_3x_1x_3\Big\rangle.$$

The right hand side ideal is clearly contained in $J^{f,[Z_1]}$, hence it is enough to show that both ideals have the same Hilbert function. If $A_1\neq 0$ then the leading terms ideal of the right hand side ideal is

$$\langle x_0^2,\ x_1^2,\ x_2^2,\ x_3^2,\ x_0x_1,\ x_2x_3,\ x_1x_2,\ x_0x_2,\ x_0x_3\rangle$$

whose quotient ring has Hilbert function equal to 1, 4, 1 and 0 for degree bigger than 2. If $A_1=0$, the leading terms ideal is

$$\langle x_0^2,\ x_1^2,\ x_2^2,\ x_3^2,\ x_0x_1,\ x_2x_3,\ x_1x_3,\ x_0x_2,\ x_0x_3\rangle$$

whose quotient ring also has Hilbert function equal to 1, 4, 1 and 0 for degree bigger than 2. Thus we are reduced to show that $R^{f,[Z_1]}$ has the same Hilbert function. Since $J^{f,[Z_1]}$ is Artinian Gorenstein of socle in degree 2 we just need to show that $J_1^{f,[Z_1]}=0$, which follows from [16, Proposition 2.1]. The statement about the quadratic fundamental form follows from Theorem 4.1 item (i) and the fact that $q_1|_{\mathrm{Sym}^2(J^{f,[Z_1]})}$ vanishes in degree ≤ 2. ■

Proposition 5.3. In the context of Example 5.2 let $d=4$, $n\geq 2$ and $m=\frac{n}{2}-2$. The Artinian Gorenstein ideal $J^{F,[Z]}$ associated to the algebraic cycle Z is

$$J^{F,[Z]}=\Big\langle \{x_{2j+1}^3\}_{j=0}^{\frac{n}{2}},\ \{x_{2j}-\zeta_8x_{2j+1}\}_{j=2}^{\frac{n}{2}},\ x_0x_1^2,\ x_2x_3^2,\ A_1x_1^2x_2x_3+A_2x_1^2x_3^2,$$
$$x_0x_2+B_1x_1x_2+B_2x_1x_3,\ x_0x_3+C_1x_1x_2+C_2x_1x_3,$$
$$x_0^2+D_1x_0x_1+D_2x_1^2,\ x_2^2+E_1x_2x_3+E_2x_3^2\Big\rangle$$

where $(A_1 : A_2) = (r\zeta_8^2 + \check{r}\zeta_8^{\alpha_0+\alpha_2} : -(r\zeta_8^3 + \check{r}\zeta_8^{\alpha_0+2\alpha_2})) \in \mathbb{P}^1$,

$$B_1 = \frac{\zeta_8^2 - \zeta_8^{\alpha_0+\alpha_2}}{\zeta_8^{\alpha_2} - \zeta_8},\ B_2 = \frac{\zeta_8(\zeta_8^{\alpha_0+\alpha_2} - \zeta_8^{\alpha_2+1})}{\zeta_8^{\alpha_2} - \zeta_8},\ C_1 = \frac{\zeta_8 - \zeta_8^{\alpha_0}}{\zeta_8^{\alpha_2} - \zeta_8},\ C_2 = \frac{\zeta_8(\zeta_8^{\alpha_0} - \zeta_8^{\alpha_2})}{\zeta_8^{\alpha_2} - \zeta_8},$$

$$D_1 = \frac{-(\zeta_8^{2(\alpha_0+1)} + 1)}{\zeta_8^2(\zeta_8^{\alpha_0} - \zeta_8)},\ D_2 = \frac{\zeta_8^{\alpha_0}(1 + \zeta_8^{\alpha_0+3})}{\zeta_8^2(\zeta_8^{\alpha_0} - \zeta_8)},\ E_1 = \frac{-(\zeta_8^{2(\alpha_2+1)} + 1)}{\zeta_8^2(\zeta_8^{\alpha_2} - \zeta_8)},\ E_2 = \frac{\zeta_8^{\alpha_2}(1 + \zeta_8^{\alpha_2+3})}{\zeta_8^2(\zeta_8^{\alpha_2} - \zeta_8)}.$$

In particular, the degree $k := n + 6$ piece of the quadratic fundamental form vanishes.

Proof As in the other cases, we are reduced to show that

$$\begin{aligned} J^{f,[Z_1]} =\Big\langle & x_1^3,\ x_3^3,\ x_0x_1^2,\ x_2x_3^2,\ A_1x_1^2x_2x_3 + A_2x_1^2x_3^2, \\ & x_0x_2 + B_1x_1x_2 + B_2x_1x_3,\ x_0x_3 + C_1x_1x_2 + C_2x_1x_3, \\ & x_0^2 + D_1x_0x_1 + D_2x_1^2,\ x_2^2 + E_1x_2x_3 + E_2x_3^2\Big\rangle. \end{aligned}$$

The right hand side ideal is clearly contained in $J^{f,[Z_1]}$. Let us assume that $A_1 \neq 0$ (the case $A_1 = 0$ is analogue), taking the ideal generated by the leading terms in the lexicographical monomial ordering we get

$$\langle x_0^2,\ x_2^2,\ x_0x_2,\ x_0x_3,\ x_1^3,\ x_3^3,\ x_0x_1^2,\ x_2x_3^2,\ x_1^2x_2x_3\rangle \subseteq \mathrm{LT}(J^{f,Z_1}).$$

For the left monomial ideal, the quotient ring has Hilbert function $1, 4, 6, 4, 1$ and 0 for degree bigger than 4. Thus it is enough to show that $J_1^{f,[Z_1]} = 0$ and $\dim\ J_2^{f,[Z_1]} = 4$. For this we use again [16, Proposition 2.1] and check that

$$J_1^{f,[Z_1]} = \langle x_0 - \zeta_8x_1, x_2 - \zeta_8x_3\rangle_1 \cap \langle x_0 - \zeta_8^{\alpha_0}x_1, x_2 - \zeta_8^{\alpha_2}x_3\rangle_1 = 0$$

and

$$J_2^{f,[Z_1]} = \langle x_0 - \zeta_8x_1, x_2 - \zeta_8x_3\rangle_2 \cap \langle x_0 - \zeta_8^{\alpha_0}x_1, x_2 - \zeta_8^{\alpha_2}x_3\rangle_2$$

$$= \langle (x_0-\zeta_8x_1)(x_0-\zeta_8^{\alpha_0}x_1), (x_2-\zeta_8x_3)(x_0-\zeta_8^{\alpha_0}x_1), (x_0-\zeta_8x_1)(x_2-\zeta_8^{\alpha_2}x_3), (x_2-\zeta_8x_3)(x_2-\zeta_8^{\alpha_2}x_3)\rangle_2.$$

The statement about the quadratic fundamental forms follows from Theorem 4.1 item (i) and the verification that the quadratic fundamental form $q_1|_{\mathrm{Sym}^2(J^{f,[Z_1]})}$ vanishes in degree ≤ 4. ■

With the same notation of Example 5.2, the last remaining case to analyze is $m = \frac{n}{2} - 1$ and $r \neq \check{r}$. In this case we are not giving a full description of the generators of the Artinian Gorenstein ideal, but instead we provide an element where the quadratic fundamental never vanishes for $d \geq 2 + \frac{8}{n}$.

Theorem 5.1. For $d \geq 2 + \frac{8}{n}$, $m = \frac{n}{2} - 1$ and $r \neq \check{r}$, the degree $k = d + (d-2)(\frac{n}{2} + 1)$ piece of the quadratic fundamental form associated to the Hodge locus $V_{r[\mathbb{P}^{\frac{n}{2}}] + \check{r}[\check{\mathbb{P}}^{\frac{n}{2}}]}$ does not vanish at the Fermat point. In consequence $V_{r[\mathbb{P}^{\frac{n}{2}}] + \check{r}[\check{\mathbb{P}}^{\frac{n}{2}}]}$ is not smooth.

Proof The condition $d \geq 2 + \frac{8}{n}$ allows use to use Theorem 4.1 item (ii) applied for $e = d$, $\ell = d-2$ and $j = k = 0$, to reduce the theorem to show that $q_1|_{\mathrm{Sym}^2(J^{f,[Z_1]})}$ is non-zero in degree $d-2$. Consider

$$G := x_1^{d-3}((r\zeta_{2d} + \check{r}\zeta_{2d}^{\alpha_0})x_0 + (r\zeta_{2d}^2 + \check{r}\zeta_{2d}^{2\alpha_0})x_1) \in J_{d-2}^{f,[Z_1]}.$$

The quadratic fundamental form at G is

$$q_1(G,G) = r\check{r}\zeta_{2d}^{\alpha_0+1}(\zeta_{2d}^{\alpha_0}-\zeta_{2d})^2 x_0^{d-4}x_1^{d-3}\{(r[\zeta_{2d}^2(d-1)+\zeta_{2d}^{\alpha_0+1}]+\check{r}[\zeta_{2d}^{2\alpha_0}(d-1)+\zeta_{2d}^{\alpha_0+1}])x_0$$
$$+(r[(d-1)\zeta_{2d}^2(\zeta_{2d}^{\alpha_0}+\zeta_{2d})+2\zeta_{2d}^{2\alpha_0+1}]+\check{r}[(d-1)\zeta_{2d}^{2\alpha_0}(\zeta_{2d}^{\alpha_0}+\zeta_{2d})+2\zeta_{2d}^{\alpha_0+2}])x_1\}.$$

In order to see that this is non-zero in $R^f/\langle P_{Z_1}\rangle$, let us note first that $\langle P_{Z_1}\rangle_{2d-6}$ is a 2-dimensional subspace of R^f_{2d-6}. In fact, in the basis of $R^f_{2d-6}=\mathbb{C}\cdot x_0^{d-2}x_1^{d-4}\oplus\mathbb{C}\cdot x_0^{d-3}x_1^{d-3}\oplus\mathbb{C}\cdot x_0^{d-4}x_1^{d-2}$

$$\langle P_{Z_1}\rangle_{2d-6}=\mathbb{C}\cdot Q_1\oplus\mathbb{C}\cdot Q_2$$

where

$$Q_1=(r\zeta_{2d}+\check{r}\zeta_{2d}^{\alpha_0})x_0^{d-2}x_1^{d-4}+(r\zeta_{2d}^2+\check{r}\zeta_{2d}^{2\alpha_0})x_0^{d-3}x_1^{d-3}+(r\zeta_{2d}^3+\check{r}\zeta_{2d}^{3\alpha_0})x_0^{d-4}x_1^{d-2},$$
$$Q_2=(r\zeta_{2d}^2+\check{r}\zeta_{2d}^{2\alpha_0})x_0^{d-2}x_1^{d-4}+(r\zeta_{2d}^3+\check{r}\zeta_{2d}^{3\alpha_0})x_0^{d-3}x_1^{d-3}+(r\zeta_{2d}^4+\check{r}\zeta_{2d}^{4\alpha_0})x_0^{d-4}x_1^{d-2}.$$

Hence $q_1(G,G)$ vanishes if and only if $q_1(G,G)$, Q_1 and Q_2 are linearly dependent in R^f_{2d-6}. Using the monomial basis of R^f_{2d-6} we can write a 3×3 matrix M whose columns correspond to $q_1(G,G)$, Q_1 and Q_2. Computing its determinant we obtain

$$\det(M)=\pm\zeta_{2d}^{3\alpha_0+3}(\zeta_{2d}^{\alpha_0}-\zeta_{2d})^3r^2\check{r}^2(r-\check{r})$$

which is non-zero for $r\neq\check{r}$. ■

Remark 5.1. This result was already pointed out by Movasati in [9, Theorem 18.3] for a finite number of examples. In the case of surfaces Dan [1] showed that these Hodge loci are non reduced but with reduced structure equal to $V_{[\mathbb{P}^1]}\cap V_{[\check{\mathbb{P}}^1]}$ at a general surface. The higher dimensional case has also been studied recently by Kloosterman (in an upcoming article [6]) who has shown that $V_{r[\mathbb{P}^{\frac{n}{2}}]+\check{r}[\check{\mathbb{P}}^{\frac{n}{2}}]}$ is smooth for $n\geq 4$ and coincides with $V_{[\mathbb{P}^{\frac{n}{2}}]}\cap V_{[\check{\mathbb{P}}^{\frac{n}{2}}]}$ at a general hypersurface. Kloosterman result together with ours imply that $V_{r[\mathbb{P}^{\frac{n}{2}}]+\check{r}[\check{\mathbb{P}}^{\frac{n}{2}}]}$ is globally reducible (as a scheme), and more than one irreducible component is passing through the Fermat point.

6 Hilbert function associated to a Hodge cycle

Theorem 1.1 gives us the tensor product structure of the Artinian Gorenstein algebra associated to a join algebraic cycle. This structure helps us to study its associated Hilbert function.

Definition 6.1. Let $X=\{F=0\}\subseteq\mathbb{P}^{n+1}$ be a smooth degree d hypersurface of even dimension n. For every $\lambda\in H^{\frac{n}{2},\frac{n}{2}}(X,\mathbb{Q})$, its associated *Hilbert function* $\mathrm{HF}_\lambda:\mathbb{Z}_{\geq 0}\to\mathbb{Z}_{\geq 0}$ is the Hilbert function of its associated Artinian Gorenstein algebra $R^{F,\lambda}=\mathbb{C}[x_0,\dots,x_{n+1}]/J^{F,\lambda}$.

Corollary 6.1. In the same context of Theorem 3.1 we have $\mathrm{HF}_{[J(Z_1,Z_2)]}=\mathrm{HF}_{[Z_1]}*\mathrm{HF}_{[Z_2]}$, this means that for all $k\geq 0$

$$\mathrm{HF}_{[J(Z_1,Z_2)]}(k)=\sum_{p+q=k}\mathrm{HF}_{[Z_1]}(p)\cdot\mathrm{HF}_{[Z_2]}(q). \tag{17}$$

Proof This follows from Theorem 1.1. ∎

Example 6.1. Using the above corollary we can compute the Hilbert function of the examples inside Fermat described in the previous section. As an illustration for one linear cycle in Fermat (see Example 5.1) we get

$$\mathrm{HF}_{[\mathbb{P}^{\frac{n}{2}}]} = \varphi^{*(\frac{n}{2}+1)} \tag{18}$$

where $\varphi : \mathbb{Z}_{\geq 0} \to \mathbb{Z}_{\geq 0}$ is the Hilbert function of a point in a 0-dimensional Fermat variety

$$\varphi(k) = \begin{cases} 1 & \text{if } 0 \leq k \leq d-2, \\ 0 & \text{otherwise.} \end{cases}$$

In other words $\mathrm{HF}_{[\mathbb{P}^{\frac{n}{2}}]}(k)$ counts the number of ways of writing k as an ordered sum of $\frac{n}{2}+1$ numbers between 0 and $d-2$.

Remark 6.1. The Hilbert function of (18) is in fact the Hilbert function of a generic linear cycle inside a smooth degree d hypersurface of even dimension n. This follows from the upper semi-continuity of the Hilbert function along the locus of hypersurfaces containing an $\frac{n}{2}$-dimensional linear cycle. In fact, the upper semi-continuity of the Hilbert function holds along the locus of hypersurfaces containing an $\frac{n}{2}$-dimensional complete intersection for any fixed multi-degree. This is a direct consequence of the explicit description of generators of the associated Artinian Gorenstein ideal which can be found in [17, Example 2.1]. In particular we can compute the Hilbert function of a generic complete intersection of type $(1, 1, \ldots, 1, k)$ by writing it as a join in Fermat. In general, for other types of algebraic cycles λ we do not know whether the Hilbert function is upper semi-continuous along V_λ or not.

7 Fake algebraic cycles

In the article [2] the authors found pathological algebraic cycles in all Fermat varieties of degree 3, 4 and 6. They were pathological in the sense that their associated Hodge loci V_λ had the biggest possible Zariski tangent space at the Fermat point without being λ the class of a linear cycle (contradicting a conjecture of Movasati). These cycles were called fake linear cycles and were constructed from an arithmetic viewpoint using the Galois action in the cohomology of the Fermat variety. Using the join construction we can have a better understanding of these cycles as explicit combinations of linear cycles. In this section we will introduce a more general notion of fake algebraic cycles, inside any smooth hypersurface and we will show how one can find hypersurfaces containing fake linear cycles in any degree.

Definition 7.1. Let $X = \{F = 0\} \subseteq \mathbb{P}^{n+1}$ be a smooth degree d hypersurface of even dimension n. Let $Z \subseteq X$ be an $\frac{n}{2}$-dimensional algebraic subvariety. A Hodge cycle $\lambda \in H^{\frac{n}{2},\frac{n}{2}}(X, \mathbb{Q})$ is a *fake version of* $[Z]$ if

$$\mathrm{HF}_\lambda = \mathrm{HF}_{[Z]}$$

but λ_{prim} is not a scalar multiple of $[Z]_{\mathrm{prim}}$.

Remark 7.1. By [2, Theorem 1.1] all Fermat varieties of degree $d=3,4,6$ (and only for those degrees) admit fake linear cycles. In fact, in this case the main result shows that $\mathrm{HF}_\lambda(d)=\binom{\frac{n}{2}+d}{d}-(\frac{n}{2}+1)^2=\mathrm{HF}_{[\mathbb{P}^{\frac{n}{2}}]}(d)$ implies

$$P_\lambda = c_\lambda \prod_{j=0}^{\frac{n}{2}}\left(\frac{x_{2j}^{d-1}-(c_jx_{2j+1})^{d-1}}{x_{2j}-c_jx_{2j+1}}\right) \tag{19}$$

for any $c_j\in\zeta_{2d}^{-3}\cdot\{z\in\mathbb{Q}(\zeta_d):\ |z|=1\}$ and some $c_\lambda\in\mathbb{Q}(\zeta_{2d})^\times$. From this we deduce that

$$J^{F,\lambda}=\langle x_0-c_0x_1,x_2-c_1x_3,\dots,x_n-c_{\frac{n}{2}}x_{n+1},x_0^{d-1},\dots,x_{n+1}^{d-1}\rangle, \tag{20}$$

which in turn implies that $\mathrm{HF}_\lambda=\mathrm{HF}_{[\mathbb{P}^{\frac{n}{2}}]}$. In the case where all c_j are d-th roots of -1, λ corresponds to the class of a linear cycle in Fermat. In all other cases λ is a fake linear cycle. The description of the Artinian Gorenstein ideal (20) implies that

$$R^{F,\lambda}=\bigotimes_{j=1}^{\frac{n}{2}+1}R^{F_j,\lambda_j}$$

where $X_j=\{F_j(x_{2j-2},x_{2j-1}):=x_{2j-2}^d+x_{2j-1}^d=0\}\subseteq\mathbb{P}^1$ and λ_j is the class of a 0-cycle such that

$$P_{\lambda_j}=\frac{x_{2j-2}^{d-1}-(c_{2j-2}x_{2j-1})^{d-1}}{x_{2j-2}-c_{2j-2}x_{2j-1}}.$$

In other words, each λ_j is a 0-dimensional fake linear cycle. Since this is a Hodge cycle, there exist $n_{j,1},\dots,n_{j,d}\in\mathbb{Q}$ such that

$$P_{\lambda_j}=\sum_{\ell=1}^{d}n_{j,\ell}\cdot P_{[p_\ell^j]}$$

where $X_j=\{p_1^j,p_2^j,\dots,p_d^j\}\subseteq\mathbb{P}^1$ (note that each $p_\ell^j\in\mathrm{CH}^0(X_j)$ is a linear cycle, and so we know how to compute $P_{[p_\ell^j]}$). It follows from Theorem 1.1 that

$$\lambda_{\mathrm{prim}}=c\cdot J(\lambda_1,\lambda_2,\dots,\lambda_{\frac{n}{2}+1})$$

for some $c\in\mathbb{Q}^\times$. In other words, every fake linear cycle is a linear combination of linear cycles given by

$$\lambda=\sum_{\ell_1,\ell_2,\dots,\ell_{\frac{n}{2}+1}=1}^{d}\left(\prod_{j=1}^{\frac{n}{2}+1}n_{j,\ell_j}\right)\cdot J(p_{\ell_1}^1,p_{\ell_2}^2,\dots,p_{\ell_{\frac{n}{2}+1}}^{\frac{n}{2}+1}).$$

Remark 7.2. The previous remark shows that the presence of fake linear cycles in degree $d=3,4,6$ Fermat varieties is due to their existence in 0-dimensional Fermat varieties of such degrees. Using this observation one can go further and produce some fake versions of other algebraic cycles obtained as joins. For instance we can produce fake versions of complete intersection cycles of type $(1,1,\dots,1,2)$ in Fermat varieties of degree $d=3,4,6$ by taking

$$\lambda=J(\lambda_1,[Z_2])$$

where λ_1 is a fake linear cycle in $X_1 = \{x_0^d + \cdots + x_{n-1}^d = 0\}$ and $Z_2 = p_1 + p_2 \in \mathrm{CH}^0(X_2)$ for $X_2 = \{x_n^d + x_{n+1}^d = 0\} = \{p_1, p_2, \ldots, p_d\}$. More generally, for any algebraic cycle given as a cone

$$Z = J(pt, Z_2)$$

we can construct a fake version of Z if we replace the point by a 0-dimensional fake linear cycle. Hence it is natural ask whether there are more 0-dimensional hypersurfaces (of higher degree) containing 0-dimensional fake linear cycles. It turns out that it is not hard to construct hypersurfaces with infinitely many fake linear cycles in any degree.

Theorem 7.1. Let $X = \{F(x_0, x_1) := (x_0 - r_1 x_1)(x_0 - r_2 x_1)\cdots(x_0 - r_d x_1) = 0\} \subseteq \mathbb{P}^1$ be a smooth degree d hypersurface with $r_i \in \mathbb{Q}$ for all $i = 1, \ldots, d$. Consider for each $c \in \mathbb{Q} \setminus \{r_1, \ldots, r_d\}$ the polynomial

$$P := \frac{a\frac{\partial F}{\partial x_0} - b\frac{\partial F}{\partial x_1}}{x_0 - cx_1} \in R^F_{d-2} \tag{21}$$

for $a = \frac{\partial F}{\partial x_1}(c, 1)$ and $b = \frac{\partial F}{\partial x_0}(c, 1)$. Then

$$\delta := \mathrm{res}\left(\frac{P \cdot (x_0 dx_1 - x_1 dx_0)}{F}\right) \in H^0(X, \mathbb{Q})_{\mathrm{prim}} \tag{22}$$

is a 0-dimensional fake linear cycle.

Proof For each point $p_i := (r_i : 1) \in X$ we know $[p_i]_{\mathrm{prim}} \in H^0(X, \mathbb{Q})$. Moreover we can write it as a residue applying [16, Theorem 1.1]

$$[p_i]_{\mathrm{prim}} = \frac{-1}{d}\mathrm{res}\left(\frac{P_i \cdot (x_0 dx_1 - x_1 dx_0)}{F}\right) \in H^0(X, \mathbb{Q})_{\mathrm{prim}}$$

where

$$P_i = \det\begin{pmatrix} 1 & \frac{\frac{\partial F}{\partial x_0}}{x_0 - r_i x_1} - \frac{F}{(x_0 - r_i x_1)^2} \\ -r_i & \frac{\frac{\partial F}{\partial x_1}}{x_0 - r_i x_1} + r_i \frac{F}{(x_0 - r_i x_1)^2} \end{pmatrix} = \frac{r_i \frac{\partial F}{\partial x_0} + \frac{\partial F}{\partial x_1}}{x_0 - r_i x_1} \in \mathbb{Q}[x_0, x_1]_{d-2}. \tag{23}$$

Since all the points $[p_1]_{\mathrm{prim}}, \ldots, [p_d]_{\mathrm{prim}}$ generate the $\mathbb{Q}$-vector space $H^0(X, \mathbb{Q})_{\mathrm{prim}}$ of dimension $d-1$, and the residue map is an isomorphism of $\mathbb{C}[x_0, x_1]_{d-2} = R^F_{d-2} \simeq H^0(X, \mathbb{C})_{\mathrm{prim}}$, it follows that the polynomials $P_1, \ldots, P_d$ generate all $\mathbb{Q}[x_0, x_1]_{d-2}$ as $\mathbb{Q}$-vector space. In particular, since $c \in \mathbb{Q}$, then $P \in \mathbb{Q}[x_0, x_1]_{d-2}$ and so we can write it as a $\mathbb{Q}$-linear combination

$$P = q_1 \cdot P_1 + \cdots + q_d \cdot P_d.$$

Hence $\delta = q_1 \cdot [p_1]_{\mathrm{prim}} + \cdots + q_d \cdot [p_d]_{\mathrm{prim}} \in H^0(X, \mathbb{Q})_{\mathrm{prim}}$ is a rational class. To see that it defines a fake linear cycle it is enough to see that

$$J^{F,\delta} = (J^F : P) = \langle x_0 - cx_1, x_0^{d-1}, x_1^{d-1}\rangle$$

and so $\mathrm{HF}_\delta = \mathrm{HF}_{[p_i]}$. ■

Now, as a corollary of Theorem 7.1 we obtain Theorem 1.2.

Proof of Theorem 1.2 Pick any degree d homogeneous polynomials $F_0, \dots, F_{\frac{n}{2}} \in \mathbb{Q}[x, y]_d$ such that each F_i has only simple rational roots. Define $X := \{F_0(x_0, x_1) + F_1(x_2, x_3) + \cdots + F_{\frac{n}{2}}(x_n, x_{n+1}) = 0\} \subseteq \mathbb{P}^{n+1}$. For each $i = 0, \dots, \frac{n}{2}$ consider $X_i := \{F_i(x_{2i}, x_{2i+1}) = 0\} \subseteq \mathbb{P}^1$ and take any fake linear cycle $\delta_i \in H^0(X_i, \mathbb{Q})_{\mathrm{prim}}$. Then by Corollary 6.1

$$\delta := J(\delta_0, \dots, \delta_{\frac{n}{2}}) \in H^{\frac{n}{2}, \frac{n}{2}}(X, \mathbb{Q})_{\mathrm{prim}}$$

is a fake linear cycle. ■

Remark 7.3. A consequence of Theorem 7.1 and [17, Theorem 1.1] is that no automorphism of $\mathbb{P}^1$ transforms all points of the Fermat variety $X = \{x_0^d + x_1^d = 0\} \subseteq \mathbb{P}^1$ into rational points for $d \neq 3, 4, 6$. On the other hand, it is easy to check that for degrees $d = 3, 4, 6$ there exists an automorphism of $\mathbb{P}^1$ taking all Fermat points to rational points. This explains the presence of fake linear cycles in Fermat varieties of such degrees.

Example 7.1. Let $X = \{F(x_0, x_1) := (x_0 - r_1 x_1)(x_0 - r_2 x_1) \cdots (x_0 - r_6 x_1) = 0\} \subseteq \mathbb{P}^1$ with $r_1 = 0$, $r_2 = 1$, $r_3 = \frac{1}{2}$, $r_4 = \frac{1}{4}$, $r_5 = \frac{1}{3}$, $r_6 = \frac{2}{5}$. Consider the same notation of Theorem 7.1, and take the fake linear cycle δ of the form (22) where the polynomial P in (21) is defined using the number $c = -1$. Let P_i be the associated polynomial to the point $(r_i : 1) \in X$ for $i = 1, \dots, 5$ (this is computed explicitly in (23)). Once we know explicitly all these polynomials, it is an elementary linear algebra problem to find the $\mathbb{Q}$-linear combination of the polynomial P in terms of the polynomials $P_1, \dots, P_5$, which is

$$P = -\frac{207283}{810} P_1 - \frac{68941}{270} P_2 - \frac{507311}{1620} P_3 - \frac{26911}{180} P_4 - \frac{891881}{1620} P_5.$$

For the case of fake linear cycles in Fermat varieties of degree $d = 3, 4, 6$ one first transforms the Fermat equation to one with only rational roots, and proceeds in the same way as before. In fact, the above example is isomorphic to the Fermat sextic under the composition of the following automorphisms of $\mathbb{P}^1$

$$\phi(x_0 : x_1) = (x_0 : x_0 + x_1)$$
$$\psi(x_0 : x_1) = (x_0 - \zeta_{12} x_1 : (1 + \zeta_6^{-1})(x_0 - \zeta_{12}^{3} x_1)).$$

We have that $\psi^* \phi^*(F) = -\frac{2\zeta_6^2 + 1}{40}(x_0^6 + x_1^6)$ and the 0-dimensional fake linear cycle $\delta \in H^0(X, \mathbb{Q})_{\mathrm{prim}}$ is transformed to the fake linear cycle $\lambda = \psi^* \phi^* \delta$ inside the Fermat variety $\{x_0^6 + x_1^6 = 0\} \subset \mathbb{P}^1$ given by

$$\lambda = \mathrm{res}\left(\frac{P_\lambda \cdot (x_0 dx_1 - x_1 dx_0)}{x_0^6 + x_1^6} \right)$$

with

$$P_\lambda = c_\lambda \frac{x_0^5 - (c_0 x_1)^5}{x_0 - c_0 x_1},$$

where $c_0 = \zeta_{12}^{-3} \left(\frac{3\zeta_6^2 - 1}{3 - \zeta_6^2} \right) \in \zeta_{12}^{-3} \cdot \mathbb{S}^1_{\mathbb{Q}(\zeta_6)}$ and $c_\lambda = \frac{\zeta_{12}(191\zeta_6 + 146)}{1 - 2\zeta_6} \in \mathbb{Q}(\zeta_{12})^\times$.

As a final result of this section we show the non smoothness of the Hodge loci associated to fake linear cycles.

Theorem 7.2. Let n an even number and $d \geq 2 + \frac{6}{n}$ an integer. For any degree d homogeneous polynomials $F_0, \dots, F_{\frac{n}{2}} \in \mathbb{Q}[x,y]_d$ with no multiple roots, let

$$X = \{F_0(x_0,x_1) + F_1(x_2,x_3) + \cdots + F_{\frac{n}{2}}(x_n,x_{n+1}) = 0\} \subseteq \mathbb{P}^{n+1}.$$

For each $i = 0, \dots, \frac{n}{2}$ consider $X_i := \{F_i(x_{2i},x_{2i+1}) = 0\} \subseteq \mathbb{P}^1$ and some $\delta_i \in H^0(X_i,\mathbb{Q})_{\text{prim}}$ with HF_{δ_i} equal to the Hilbert function of a point. Let $\delta := J(\delta_1, \dots, \delta_{\frac{n}{2}})$, then δ is a fake linear cycle if and only if V_δ is not smooth.

Proof If all δ_i are the primitive classes of points (up to scalar multiplication), then δ is the primitive class of a linear cycle (up to scalar multiplication), and so V_δ is known to be smooth. If some δ_i is a 0-dimensional fake linear cycle, then we can write (up to scalar multiplication) $\delta_i = \text{res}\left(\frac{P\cdot(x_{2i}dx_{2i+1} - x_{2i+1}dx_{2i})}{F_i}\right)$ for

$$P = \frac{a\frac{\partial F_i}{\partial x_{2i}} - b\frac{\partial F_i}{\partial x_{2i+1}}}{x_{2i} - cx_{2i+1}}$$

where $a = \frac{\partial F_i}{\partial x_{2i+1}}(c,1)$, $b = \frac{\partial F_i}{\partial x_{2i}}(c,1)$ and $F_i(c,1) \neq 0$. If we compute the quadratic fundamental form q_i of V_{δ_i} at the term $x_{2i} - cx_{2i+1} \in J_1^{F_i,\delta_i}$ we get

$$q_i(x_{2i} - cx_{2i+1}, x_{2i} - cx_{2i+1}) = a + bc = d \cdot F_i(c,1) \neq 0.$$

We claim that $R^{F_i}/\langle P\rangle$ is non-zero at degree $2d-5$. In fact, since J^{F_i} is Artinian Gorenstein of socle in degree $2d-4$, then $(J^{F_i} : x_{2i} - cx_{2i+1})$ is Artinian Gorenstein of socle in degree $2d-5$ and so there exists some $Q \in \mathbb{C}[x_{2i},x_{2i+1}]_{2d-5}$ such that $Q \cdot (x_{2i} - cx_{2i+1}) \notin J^{F_i}$. But since $P \cdot (x_{2i} - cx_{2i+1}) \in J^{F_i}$, it follows that $Q \notin \langle P\rangle$, and so $(R^{F_i}/\langle P\rangle)_{2d-5} \neq 0$ as claimed. Therefore

$$q_i|_{\text{Sym}^2(J_1^{F_i,\delta_i})} \cdot \mathbb{C}[x_{2i},x_{2i+1}]_{2d-5} \neq 0 \in R^{F_i}/\langle P\rangle.$$

Using that $d \geq 2 + \frac{6}{n}$ we can apply Theorem 4.1 (ii) with the values $e = d$, $\ell = 1$, $j = 2d-5$, $k = 0$ to conclude that the quadratic fundamental form q associated to V_δ is non-zero in degree d, and so V_δ is not smooth. ∎

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