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On divisibility of exponential sums of polynomials of special type over fields of characteristic 2 ^{*}

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Abstract. We study divisibility by eight of exponential sums of several classes of functions over finite fields of characteristic two. For the binary classical Kloosterman sums $K(a)$ over such fields we give a simple recurrent algorithm for finding the largest k , such that 2^k divides the Kloosterman sum $K(a)$. This gives a simple description of zeros of such Kloosterman sums.

Keywords: exponential sum, Kloosterman sum, divisibility by power of two, zero of Kloosterman sum

1. Introduction. Let $\mathbb{F} = \mathbb{F}_{2^m}$ be the field of characteristic 2 of order 2^m , where $m \geq 3$ is an integer. By \mathbb{F}_2 denote the field, consisting of two elements. Set

$$e(x) = (-1)^{Tr(x)}, \quad x \in \mathbb{F},$$

where $Tr(x)$ is the trace function from \mathbb{F} into \mathbb{F}_2 . For an arbitrary polynomial $f(x)$ over \mathbb{F} define its exponential sum $S(f)$,

$$S(f) = \sum_{x \in \mathbb{F}} e(f(x)).$$

Recall that under x^{-i} we understand x^{2^m-1-i} , avoiding by this way a division into 0. The sum

$$K(a) = \sum_{x \in \mathbb{F}} e(x + a/x), \quad a \in \mathbb{F}^*,$$

is called the *Kloosterman sum*.

Given a polynomial $f(x)$ over \mathbb{F} it is a hard mathematical problem to write out the value of its exponential sum $S(f)$ or the module $|S(f)|$. This problem is interesting from several points of view, for example, for the theory of error-correcting codes, for sequences, for solving of equations over finite fields, for

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cryptography and etc. In some cases the value $S(f)$ is known (see [1], [2], [8] and references there). From this point of view, the divisibility of $S(f)$ is an interesting important open problem. Recently, the divisibility of $K(a)$ has been considered in several papers. In particular, the divisibility of $K(a)$ modulo 24 has been solved in [4], and the divisibility by 16 has been solved in [9].

In the present paper we use an elementary combinatorial approach to study divisibility by eight of exponential sums of polynomials of special type (such as $a(x^d + x^{-d})$, $ax^d + bx^{-1}$, $a(x + x^{-1})^d$, and etc.). This is considered in the first three sections. In the last section we consider the divisibility of Kloosterman sums $K(a)$ into the maximal power of two, which results in a simple algorithm of finding of zeros of Kloosterman sums. Kloosterman zeros play a significant role in construction of highly nonlinear functions that are used in cryptography, in particular, for construction of *bent functions* (see [5], [6]) and *hyperbent functions* (see [5]).

2. Polynomials of type $a(x^d + x^{-d})$. We start by studying the divisibility by 8 of exponential sums of polynomials $f(x)$ of the type

$$f(x) = a(x^d + x^{-d}), \quad a \in \mathbb{F}^*,$$

where d is any odd integer, $1 \leq d \leq 2^m - 3$. All our proofs of divisibility by eight are based on the following quite evident observation.

Proposition 1 . *Let $\mathbf{b} = (b_1, \dots, b_k, b_{k+1}, \dots, b_{2k})$ be a binary sequence of even length $2k$, and let $\mathbf{b}_{inv} = (b_{2k}, \dots, b_{k+1}, b_k, \dots, b_1)$ be the inverse sequence. Then the Hamming distance*

$$d(\mathbf{b}, \mathbf{b}_{inv}) \equiv \begin{cases} 0 \pmod{4}, & \text{if } \text{wt}(\mathbf{b}) \text{ even,} \\ 2 \pmod{4}, & \text{if } \text{wt}(\mathbf{b}) \text{ odd,} \end{cases}$$

where $\text{wt}(\mathbf{b})$ is the Hamming weight of \mathbf{b} (i.e. the number of ones in the sequence \mathbf{b}).

Let β be a primitive element of \mathbb{F} . For a given $a \in \mathbb{F}^*$ and an odd integer d , $1 \leq d \leq 2^m - 3$, define a binary vector of length 2^m :

$$\mathbf{T}(ax^d) = (\text{Tr}(0), \text{Tr}(a), \text{Tr}(a\beta^d), \text{Tr}(a\beta^{2d}), \dots, \text{Tr}(a\beta^{(2^m-2)d})).$$

In the similar way define the vector $\mathbf{T}(ax^{-d})$ of the same length. Denote

$$\mathbf{T}_1(ax^d) = (\text{Tr}(a\beta^d), \text{Tr}(a\beta^{2d}), \dots, \text{Tr}(a\beta^{(2^{m-1}-1)d}))$$

and

$$\mathbf{T}_2(ax^d) = (\text{Tr}(a\beta^{2^{m-1}d}), \text{Tr}(a\beta^{(2^{m-1}+1)d}), \dots, \text{Tr}(a\beta^{(2^m-2)d})).$$

Similarly define also the vectors $\mathbf{T}_1(ax^{-d})$ and $\mathbf{T}_2(ax^{-d})$. Note that the vector $(\mathbf{T}_1(ax^{-d}), \mathbf{T}_2(ax^{-d}))$ of length $2^m - 2$ is an inversion of the vector

$$(\mathbf{T}_1(ax^d), \mathbf{T}_2(ax^d)).$$

Since

$$\sum_{x \in \mathbb{F}} \text{Tr}(a x^d) = \text{Tr} \left(\sum_{i=0}^{2^m-2} a \beta^{i d} \right) = \text{Tr} \left(a \frac{\beta^{d(2^m-1)} - 1}{\beta - 1} \right) = 0,$$

the weight of the vector $(\mathbf{T}_1(a x^d), \mathbf{T}_2(a x^d))$ is even, if $\text{Tr}(a) = 0$. The same property is valid for the vector $(\mathbf{T}_1(a x^{-d}), \mathbf{T}_2(a x^{-d}))$. But if $\text{Tr}(a) = 1$, then the corresponding weights are odd. Therefore, according to Proposition 1 we obtain that

$$d(\mathbf{T}(a x^d), \mathbf{T}(a x^{-d})) \equiv \begin{cases} 0 & (\text{mod } 4), \text{ if } \text{Tr}(a) = 0, \\ 2 & (\text{mod } 4), \text{ if } \text{Tr}(a) = 1. \end{cases}$$

Since

$$S(a(x^d + x^{-d})) = 2^m - 2 d(\mathbf{T}(a x^d), \mathbf{T}(a x^{-d})),$$

the following result holds.

Statement 1 . Let $a \in \mathbb{F}^*$, and d be any odd integer, $1 \leq d \leq 2^m - 3$. Then

$$S(a(x^d + x^{-d})) \equiv \begin{cases} 0 & (\text{mod } 8), \text{ if } \text{Tr}(a) = 0, \\ 4 & (\text{mod } 8), \text{ if } \text{Tr}(a) = 1. \end{cases}$$

The proof given above is quite elementary. Remark, that this result was known for $d = 1$ and, therefore, for any d which is relatively prime to $2^m - 1$ (see [7], where two proofs of this result are given: the first one based on finding of the number of solutions of some system of equations over \mathbb{F} , and the second one, suggested by P. Charpin, based on Melas codes).

It is easy to see that the sum $S(a(x^d + x^{-d}))$ depends on the value of the greatest common divisor $h = (d, 2^m - 1)$ of numbers d and $2^m - 1$. In particular, h divides $S(a(x^d + x^{-d})) - 1$. Indeed, denoting $2^m - 1 = hu$, we obtain

$$\begin{aligned} S(a(x^d + x^{-d})) &= 1 + \sum_{i=0}^{2^m-2} e(a(\beta^{i d} + \beta^{-i d})) \\ &= 1 + \sum_{i=0}^{2^m-2} e(a \beta^{i d}) e(a \beta^{-i d}) \\ &= 1 + \sum_{j=0}^{u-1} \sum_{s=0}^{h-1} e(a(\beta^{(j+s u) d}) e(a \beta^{-(j+s u) d}) \\ &= 1 + \sum_{j=0}^{u-1} e(a \beta^{j d}) e(a \beta^{-j d}) \sum_{s=0}^{h-1} e(a \beta^{s u d}) e(a \beta^{-s u d}) \\ &= 1 + h \sum_{j=0}^{u-1} e(a \beta^{j d}) e(a \beta^{-j d}) \\ &= 1 + h \sum_{j=0}^{u-1} e(a(\beta^{j d} + \beta^{-j d})). \end{aligned}$$

From the last expression and Statement 1 we have the following

Statement 2 . Let d be any odd integer, $1 \leq d \leq 2^m - 3$, and $h = (d, 2^m - 1)$. For any elements $a_1, a_2 \in \mathbb{F}^*$ the following congruence is valid:

$$S(a_1(x^d + x^{-d})) - S(a_2(x^d + x^{-d})) \equiv \begin{cases} 0 & (\text{mod } 4h), \text{ if } \text{Tr}(a_1) \neq \text{Tr}(a_2), \\ 0 & (\text{mod } 8h), \text{ if } \text{Tr}(a_1) = \text{Tr}(a_2), . \end{cases}$$

From the proof of Statement 1 also follows clearly the following more general

Statement 3 . Let $a_1, \dots, a_t \in \mathbb{F}^*$ and d_1, \dots, d_t be any odd numbers, $1 \leq d_i \leq 2^m - 3$, $i = 1, \dots, t$. Then

$$S\left(\sum_{i=1}^t a_i(x^{d_i} + x^{-d_i})\right) \equiv \begin{cases} 0 & (\text{mod } 8), \text{ if } \text{Tr}\left(\sum_{i=1}^t a_i\right) = 0, \\ 4 & (\text{mod } 8), \text{ if } \text{Tr}\left(\sum_{i=1}^t a_i\right) = 1. \end{cases}$$

3. Polynomials of type $a(x + x^{-1})^d$. Now consider polynomials $f(x) = a(x + x^{-1})^d$, where

$$d = \sum_{j=0}^{\ell} 2^{d_j}$$

is any odd number, $3 \leq d \leq 2^m - 3$,

$$m > d_\ell > d_{\ell-1} > \dots > d_0 = 0$$

and $\ell \geq 1$. Clearly

$$\begin{aligned} f(x) &= a(x + x^{-1})^{\sum_{j=0}^{\ell} 2^{d_j}} \\ &= a \prod_{j=0}^{\ell} (x^{2^{d_j}} + x^{-2^{d_j}}) \\ &= \sum_k a(x^k + x^{-k}), \end{aligned}$$

where summing is taken over all k of the type

$$k = 2^{d_\ell} \pm 2^{d_{\ell-1}} \pm \dots \pm 1$$

(i.e. the value k takes 2^ℓ different values). Since $Tr(\sum_k a) = 0$ (indeed, the sum consists of even number of monoms), then according to Statement 3 (taking into account, that $a_i = a$ for all $i = 1, \dots, 2^\ell$) we obtain the following result.

Statement 4 . Let $a \in \mathbb{F}^*$ and d be any odd number, $3 \leq d \leq 2^m - 3$. Then

$$S(a(x + x^{-1})^d) \equiv 0 \pmod{8}.$$

From Statement 3 also follows more general result.

Statement 5 . Let $a_1, \dots, a_t \in \mathbb{F}^*$, d_1, \dots, d_t be any odd numbers, $3 \leq d_i \leq 2^m - 3$. Then

$$S\left(\sum_{j=1}^t a_j (x + x^{-1})^{d_j}\right) \equiv 0 \pmod{8}.$$

Remark 1 . Clearly Statement 5 is still satisfied, if we change $x + x^{-1}$ by $x^r + x^{-r}$, where r is any integer, $3 \leq r \leq 2^m - 3$.

4. Polynomials of type $ax^d + bx^{-1}$. Consider now polynomials $f(x) = ax^d + bx^{-1}$, where $a, b \in \mathbb{F}$, $a \neq 0$, and d is any odd number, $1 \leq d \leq 2^m - 3$. First prove the following statement.

Proposition 2 . Let $c \in \mathbb{F}^*$. Then

$$S(cx^d + x^{-1}) + S(cx^d) = S(c(x + x^{-1})^d).$$

Proof. The following chain of equalities takes place:

$$\begin{aligned} & S(cx^d + x^{-1}) + S(cx^d) \\ &= \sum_{\text{Tr}(x^{-1})=0} e(cx^d + x^{-1}) + \sum_{\text{Tr}(x^{-1})=1} e(cx^d + x^{-1}) \\ &+ \sum_{\text{Tr}(x^{-1})=0} e(cx^d) + \sum_{\text{Tr}(x^{-1})=1} e(cx^d) \\ &= \sum_{\text{Tr}(x^{-1})=0} e(cx^d + x^{-1}) + \sum_{\text{Tr}(x^{-1})=0} e(cx^d) \\ &= 2 \times \sum_{x \in \mathbb{F}: \text{Tr}(x^{-1})=0} e(cx^d). \end{aligned}$$

Since the equation

$$y + \frac{1}{y} = x, \quad x \in \mathbb{F} \tag{1}$$

has two distinct zeros y_1, y_2 in the field \mathbb{F} , if and only if $\text{Tr}(x^{-1}) = 0$ (see [8]) and the number of the elements $x \in \mathbb{F}$, such that $\text{Tr}(x^{-1}) = 0$, is equal to 2^{m-1} , then the solutions y_1, y_2 of the equation (1), for all such x , run over the all field \mathbb{F} . Therefore,

$$2 \times \sum_{x \in \mathbb{F}: \text{Tr}(x^{-1})=0} e(cx^d) = \sum_{y \in \mathbb{F}} e\left(c\left(y + \frac{1}{y}\right)^d\right) = S(c(x + x^{-1})^d). \quad \triangle$$

From Proposition 2 and Statement 4 the following statement follows.

Statement 6 . Let $a, b \in \mathbb{F}^*$ and d be any odd integer, $3 \leq d \leq 2^m - 3$. Then

$$S(ax^d + bx^{-1}) \equiv 0 \pmod{8},$$

if and only if

$$S(ax^d) \equiv 0 \pmod{8}.$$

Proof. Since

$$S(ax^d + bx^{-1}) = S(cx^d + x^{-1}).$$

where $c = ab^d$, and $S(cx^d) = S(ax^d)$, then, according to Proposition 2,

$$S(ax^d + bx^{-1}) = S(c(x + x^{-1})^d) - S(ax^d).$$

Now to complete the proof it is enough to use Statement 4. □

Recall that if d and $2^m - 1$ are relatively prime, then $S(ax^d) = 0$ for any element a from \mathbb{F} .

Corollary 1 . *Let $a, b \in \mathbb{F}^*$ and d be any odd integer, such that $3 \leq d \leq 2^m - 3$. If d and $2^m - 1$ are mutually prime, then*

$$S(ax^d + bx^{-1}) \equiv 0 \pmod{8}.$$

Corollary 2 . *Since $S(ax^3) \equiv 0 \pmod{8}$ for even $m \geq 6$ (see [2]), then*

$$S(ax^3 + bx^{-1}) \equiv 0 \pmod{8}, \quad a, b \in \mathbb{F}^*,$$

for even $m \geq 6$.

This result was known (see [3]).

5. Kloosterman sums. Now consider Kloosterman sums $K(a)$. Here we study the divisibility of such sums by the maximal possible number of the type 2^k (i.e. 2^k divides $K(a)$, but 2^{k+1} does not divide $K(a)$).

We are going to formulate a simple recurrent algorithm for finding the largest k , such that 2^k divides the Kloosterman sum $K(a)$. Before it, recall Lemma 7.4 in [10].

Lemma A [10]. *Let polynomials $g_i = g_i(x)$ over \mathbb{F} be defined by the following recurrent construction:*

$$\begin{aligned} g_0 &= x, \\ g_1 &= x + b_1, \quad \text{where } b_1^4 = a^2, \\ \dots & \quad \dots \quad \dots \end{aligned}$$

$$g_i = g_{i-1}^2 + b_i x \prod_{j=1}^{i-1} (g_j)^2, \quad \text{where } b_i^{2^{i+1}} = a^2 \text{ for } i \geq 2. \tag{2}$$

Then the all zeros of the polynomial g_{k-1} gives the x -th coordinates of the points of order 2^k of the elliptic curve $E(a)$ over \mathbb{F} , defined by the following equation:

$$y^2 + xy = x^3 + a^2. \tag{3}$$

Now recall the following result due to Lisonek P. (see reference in [9]), which we formulate only for $p = 2$.

Theorem B [9]). Let $a \in \mathbb{F}^*$, and let $0 \leq k \leq m$. Then $2^k | K(a)$ if and only if there exists a point of order 2^k on $E(a)$, where the curve $E(a)$ is defined by (3).

For a given element $a \in \mathbb{F}^*$, define now the sequence x_1, x_2, \dots, x_k of elements of the field \mathbb{F} by the following recurrent expression:

$$\left. \begin{aligned} x_1 &= 0, \\ x_{i+1}^2 + \sqrt{x_i} x_{i+1} + a &= 0, \quad i = 1, \dots, k-1. \end{aligned} \right\} \quad (4)$$

The following one of the main results follows from Lemma A and Theorem B.

Theorem 1 . Let a be any element of \mathbb{F}^* and let a sequence of elements x_1, x_2, \dots, x_k be constructed in accordance with recurrent relation (4). Let k be the smallest natural number, such that $\text{Tr}(x_k) = 1$. Then the Kloosterman sum $K(a)$ is divisible by 2^k and is not divisible by 2^{k+1} .

It is interesting to find a direct proof of Theorem 1, which does not use a transition to the number of rational points of the elliptic curve $E(a)$.

Corollary 3 [7]. Since $x_2 = \sqrt{a}$, then $K(a)$ is divisible by 4, but not divisible by 8, if $\text{Tr}(a) = 1$.

Corollary 4 [7], [9]. Let $\text{Tr}(a) = 0$. Then a can be presented as $a = z^8 + z^{16}$. In this case $x_3 = z^6 + z^8$. If $\text{Tr}(z) \neq \text{Tr}(z^3)$, then $K(a)$ is divisible by 8, but not divisible by 16.

Corollary 5 [9]. Under conditions of the Corollary 4 above, if $\text{Tr}(z) = \text{Tr}(z^3)$, then $K(a)$ is divisible by 16.

Recall (see [5] and references there) that the function $f_{a,r}(x)$,

$$f_{a,r}(x) = \text{Tr} \left(a x^{r(2^{m/2}-1)} \right), \quad a \in \mathbb{F}^*,$$

for even m and natural r , such that r and $2^{m/2} + 1$ are mutually prime, is bent, if and only if $K(a) = 0$, and the function $f_a(x)$

$$f_a(x) = \text{Tr} \left(a x^{2^m-1} \right), \quad a \in \mathbb{F}^*,$$

is hyperbent, if and only if $K(a) = 0$.

Theorem 1 implies the following simple necessary and sufficient condition for an element a to be a zero of the Kloosterman sum $K(a)$, i.e. in order to have $K(a) = 0$.

Theorem 2 . Let a be any element of \mathbb{F}^* and let a sequence u_1, u_2, \dots, u_m of elements from \mathbb{F} be defined in accordance with the following recurrent relation:

$$u_{i+1} = u_i^2 + \frac{a^2}{u_i^2},$$

where $u_1 \in \mathbb{F}^*$ is any element of \mathbb{F}^* , such that

$$\text{Tr}(u_1) = 1 \quad \text{and} \quad \text{Tr}\left(u_1 + \frac{a}{u_1}\right) = 0.$$

Then $K(a) = 0$, if and only if $u_m = 0$, and the all $m - 1$ elements u_1, \dots, u_{m-1} are nonzero. Furthermore, if the first zero element in the sequence u_1, u_2, \dots, u_m appears on the k th place, where $k < m$, then k is the largest integer, such that 2^k divides $K(a)$.

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