Hindawi Publishing Corporation
Journal of Inequalities and Applications
Volume 2008, Article ID 894529, 8 pages
doi:10.1155/2008/894529

Research Article

Exact Values of Bernstein n-Widths for Some Classes of Periodic Functions with Formal Self-Adjoint Linear Differential Operators

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Received 10 December 2007; Accepted 18 June 2008

Recommended by Vijay Gupta

We consider the classes of periodic functions with formal self-adjoint linear differential operators $W_p(\mathcal{L}_r)$, which include the classical Sobolev class as its special case. With the help of the spectral of linear differential equations, we find the exact values of Bernstein n-width of the classes $W_p(\mathcal{L}_r)$ in the L^p for $1 < p < \infty$.

1. Introduction and main result

Let $\mathbb{C}, \mathbb{R}, \mathbb{Z}, \mathbb{N}$, and $\mathbb{N}^+$ be the sets of all complex numbers, real numbers, integers, nonnegative integers, and positive integers, respectively. Let $\mathbb{T}$ be the unit circle realized as the interval $[0, 2\pi]$ with the points 0 and 2π identified, and as usual, let $L^q := L^q[0, 2\pi]$ be the classical Lebesgue integral space of 2π-periodic real-valued functions with the usual norm $\|\cdot\|_q$, $1 \le q \le \infty$. Denote by $\widetilde{W}_p^r$ the Sobolev space of functions $x(\cdot)$ on $\mathbb{T}$ such that the $(r-1)$st derivative $x^{(r-1)}(\cdot)$ is absolutely continuous on $\mathbb{T}$ and $x^{(r)}(\cdot) \in L^p$, $r \in \mathbb{N}$. The corresponding Sobolev class is the set

$$W_p^r := \{\widetilde{W}_p^r : \|x^{(r)}(\cdot)\|_p \le 1\}. \tag{1.1}$$

Tikhomirov [1] introduced the notion of Bernstein width of a centrally symmetric set C in a normed space X. It is defined by the following formula:

$$b_n(C, X) := \sup_L \sup\{\lambda \ge 0 : L \cap \lambda BX \subset C\}, \tag{1.2}$$

where BX is the unit ball of X and the outer supremum is taken over all subspaces $L \subset X$ such that $\dim L \geq n+1$, $n \in \mathbb{N}$.

In particular, Tikhomirov posed the problem of finding the exact value of $b_n(C;X)$, where $C = W_p^r$ and $X = L^q$, $1 \leq p,q \leq \infty$. He also obtained the first results [1] for $p = q = \infty$ and $n = 2k-1$. Pinkus [2] found $b_{2n-1}(W_p^r;L^q)$, where $p = q = 1$. Later, Magaril-Il'yaev [3] obtained the exact value of $b_{2n-1}(W_p^r;L^p)$, for $1 < p < \infty$. The latest contribution to this fields is due to Buslaev et al. [4] who found the exact values of $b_{2n-1}(W_p^r;L^q)$ for all $1 < p \leq q < \infty$.

Let

$$\mathcal{L}_r(D) = D^r + a_{r-1}D^{r-1} + \cdots + a_1 D + a_0, \quad D = \frac{d}{dt}, \tag{1.3}$$

be an arbitrary linear differential operator of order r with constant real coefficients $a_0, a_1, \ldots, a_{r-1}$. Denote by p_r the characteristic polynomial of $\mathcal{L}_r(D)$. The linear differential operator $\mathcal{L}_r(D)$ will be called formal self-adjoint if $p_r(-t) = (-1)^r p_r(t)$, for each $t \in \mathbb{C}$.

We define the function classes $W_p(\mathcal{L}_r)$ as follows:

$$W_p(\mathcal{L}_r) = \left\{x(\cdot) : x^{r-1} \in AC_{2\pi}, \|\mathcal{L}_r(D)x(\cdot)\|_p \leq 1\right\}, \tag{1.4}$$

where $1 \leq p \leq \infty$.

In this paper, we will determine the exact values of Bernstein n-width of some classes of periodic functions with formal self-adjoint linear differential operators $W_p(\mathcal{L}_r)$, which include the classical Sobolev class as its special case.

We define Q_p to be the nonlinear transformation

$$(Q_p f)(t) := |f(t)|^{p-1} \operatorname{sign} f(t). \tag{1.5}$$

The maim result of this paper is the following.

Theorem 1.1. *Assume that* $1 < p < \infty$. *Let* $\mathcal{L}_r(D)$ *be an arbitrary formal self-adjoint linear differential operators given by* (1.3). *Then, there exists a number* $N \in \mathbb{N}^+$ *such that for every* $n \geq N$:

$$b_{2n-1}(W_p(\mathcal{L}_r);L^p) = \lambda_{2n} := \lambda_{2n}(p,p,\mathcal{L}_r), \tag{1.6}$$

where λ_{2n} *is that eigenvalue* λ *of the boundary value problem*

$$\begin{gathered} \mathcal{L}_r(D)y(t) = (-1)^r \lambda^{-p} (Q_p x)(t), \\ y(t) = (Q_p \mathcal{L}_r(D)x)(t), \\ x^{(j)}(0) = x^{(j)}(2\pi), \quad y^{(j)}(0) = y^{(j)}(2\pi), \quad j = 0,1,\ldots,n-1, \end{gathered} \tag{1.7}$$

for which the corresponding eigenfunction $x(\cdot) = x_{2n}(\cdot)$ *has only* $2n$ *simple zeros on* $\mathbb{T}$ *and is normalized by the condition* $\|\mathcal{L}_r(D)x(\cdot)\|_p = 1$.

2. Proof of the theorem

First we introduce some notations and formulate auxiliary statements.

Let $\mathcal{L}_r(D)$ be an arbitrary linear differential operator (1.3). Denote the 2π-periodic kernel of $\mathcal{L}_r(D)$ by

$$\mathrm{Ker}\mathcal{L}_r(D) = \{x(\cdot) \in C^r(\mathbb{T}) : \mathcal{L}_r(D)x(t) \equiv 0\}. \tag{2.1}$$

Let μ $(0 \le \mu \le r)$ be the dimension of $\mathrm{Ker}\mathcal{L}_r(D)$ and $\{\varphi_i, \dots, \varphi_\mu\}$ an arbitrary basis in $\mathrm{Ker}\mathcal{L}_r(D)$.

$Z_c(f)$ denotes the number of zeros of f in a period, counting multiplicity, and $S_c(f)$ is the cyclic sign change count for a piecewise continuous, 2π-periodic function f [2]. Following, $(x(\cdot), \lambda)$ is called the spectral pair of (1.7) if the function $x(\cdot)$ is normalized by the condition $\|\mathcal{L}_r(D)x(\cdot)\|_p = 1$. The set of all spectral pairs is denoted by $\mathrm{SP}(p, p, \mathcal{L}_r)$. Define the spectral classes $\mathrm{SP}_{2k}(p, p, \mathcal{L}_r)$ as

$$\mathrm{SP}_{2k}(p, p, \mathcal{L}_r) = \{(x(\cdot), \lambda) \in \mathrm{SP}(p, p, \mathcal{L}_r) : S_c(x(\cdot)) = 2k\}. \tag{2.2}$$

Let $\widehat{x}_{2n}(\cdot)$ denotes the solution of the extremal problem as follows:

$$\begin{gathered}\int_0^{\pi/2n} |X(t)|^p dt \longrightarrow \sup, \\ \int_0^{\pi/2n} |\mathcal{L}_r(D)X(t)|^p dt \le 1, \\ x^{(k)}\left(\left(\frac{\pi}{2n} + (-1)^{k+1}\frac{\pi}{2n}\right)/2\right) = 0, \quad k = 0, 1, \dots, n-1,\end{gathered} \tag{2.3}$$

and the function $x_{2n}(\cdot)$ is such that $x_{2n}(t) = -x_{2n}(t - \pi/n)$ for all $t \in \mathbb{T}$:

$$x_{2n}(t) := \begin{cases} \widehat{x}_{2n}(t), & 0 \le t \le \dfrac{\pi}{2n}, \\ \widehat{x}_{2n}\left(\dfrac{\pi}{n} - t\right), & \dfrac{\pi}{2n} < t \le \dfrac{\pi}{n}. \end{cases} \tag{2.4}$$

Let us extend periodically the function $x_{2n}(t)$ onto $\mathbb{R}$, and normalize the obtained function as it is required in the definition of spectral pairs. From what has been done above, we get a function $x_{2n}(t)$ belongs to $\mathrm{SP}_{2n}(p, p, \mathcal{L}_r)$. Furthermore, by [5], which any other function from $\mathrm{SP}_{2n}(p, p, \mathcal{L}_r)$ differs from $x_{2n}(\cdot)$ only in the sign and in a shift of its argument, and there exists a number $N \in \mathbb{N}^+$ such that for every $n \ge N$, all zeros of $x_{2n}(\cdot)$ are simple, equidistant with a step equal to π/n, and $S_c(x_{2n}) = S_c(\mathcal{L}_r(D)x_{2n}) = 2n$. We denote the set of zeros (= sign variations) of $\mathcal{L}_r(D)x_{2n}$ on the period by $Q_{2n} = (\tau_1, \dots, \tau_{2n})$. Let

$$G_r(t) = \frac{1}{2\pi}\sum_{k \notin \Lambda} \frac{e^{ikt}}{p_r(ik)}, \tag{2.5}$$

where $\Lambda = \{k \in \mathbb{Z} : p_r(ik) = 0\}$ and i is the imaginary unit.

The 2π-periodic G-splines are defined as elements of the linear space

$$S(Q_{2n}, G_r) = \operatorname{span}\{\varphi_1(t), \dots, \varphi_\mu(t), G_r(t-\tau_1), \dots, G_r(t-\tau_{2n})\}. \tag{2.6}$$

As was proved in [6], if $n \geq N$, then $\dim S(Q_{2n}, G_r) = 2n$.

We assume (shifting $x(\cdot)$ if necessary) that $\mathcal{L}_r(D)\widehat{x}_{2n}(\cdot)$ is positive on $(-\pi, \pi + \pi/n)$. Let $L_{2n} := L_{2n}(r, p, p)$ denote the space of functions of the form

$$x(t) = \sum_{j=1}^{\mu} a_j\varphi_j(t) + \frac{1}{\pi}\int_{\mathbb{T}} G_r(t-\tau)\left(\sum_{i=1}^{2n} b_i y_i(\tau)\right)d\tau, \tag{2.7}$$

where $a_1, \dots, a_\mu, b_1, \dots, b_{2n} \in \mathbb{R}$, $\sum_{i=1}^{2n} b_i = 0$, $y_i(\cdot) = \chi_i(\cdot)\mathcal{L}_r(D)x_{2n}(\cdot - (i-1)\pi/n)$, and $\chi_i(\cdot)$ is the characteristic function of the interval $\Delta_i := [-\pi + (i-1)\pi/n, -\pi + i\pi/n]$, $1 \leq i \leq 2n$. Obviously, $\dim L_{2n} = 2n$ and $L_{2n} \subset W_p(\mathcal{L}_r)$.

Let us now consider exact estimate of Bernstein n-width. This was introduced in [1]. We reformulate the definition for a linear operator P mapping X to Y.

Definition 2.1 (see [2, page 149]). Let $P \in L(X, Y)$. Then the Bernstein n-width is defined by

$$b_n(P(X), Y) = \sup_{X_{n+1}} \inf_{\substack{Px \in X_{n+1} \\ Px \neq 0}} \frac{\|Px\|_Y}{\|x\|_X}, \tag{2.8}$$

where X_{n+1} is any subspace of span $\{Px : x \in X\}$ of dimension $\geq n+1$.

2.1. Lower estimate of Bernstein n-width

Consider the extremal problem

$$\frac{\|x(\cdot)\|_p^p}{\|\mathcal{L}_r(D)x(\cdot)\|_p^p} \longrightarrow \inf, \quad x(\cdot) \in L_{2n}, \tag{2.9}$$

and denote the value of this problem by α^p. Let us show that $\alpha \geq \lambda_n$, this will imply the desired lower bound for b_{2n-1}. Let $x(\cdot) \in L_{2n}$, then

$$\|\mathcal{L}_r(D)x(\cdot)\|_p^p = \sum_{i=1}^{2n}\int_{\Delta_i}\left|\sum_{i=1}^{2n} b_i y_i(t)\right|^p dt = \sum_{i=1}^{2n}\int_{\Delta_i}|b_i|^p|\mathcal{L}_r(D)x_n(t)|^p dt = \frac{1}{2n}\sum_{i=1}^{2n}|b_i|^p, \tag{2.10}$$

and by setting

$$z_i(\cdot) := \frac{1}{\pi}\int_{\mathbb{T}} G_r(\cdot - \tau)y_i(\tau)d\tau, \quad i = 1, 2, \dots, 2n, \tag{2.11}$$

we reduce problem (2.9) to the form

$$\frac{\|\sum_{j=1}^{\mu} a_j\varphi_j(\cdot) + \sum_{i=1}^{2n} b_i z_i(\cdot)\|_p^p}{(1/2n)\sum_{i=1}^{2n}|b_i|^p} \longrightarrow \inf, \qquad a_1, \dots, a_\mu, b_1, \dots, b_{2n} \in \mathbb{R}. \tag{2.12}$$

This is a smooth finite-dimensional problem. It has a solution $(\overline{a}_1,\dots\overline{a}_\mu,\overline{b}_1,\dots,\overline{b}_{2n})$, and, moreover, $(\overline{b}_1,\dots,\overline{b}_{2n})\neq 0$. According to the Lagrange multiplier rule, there exists a $\eta\in\mathbb{R}$ such that the derivatives of the function $(a_1,\dots,a_\mu,b_1,\dots,b_{2n})\to g(a_1,\dots,a_\mu,b_1,\dots,b_{2n})+\eta(b_1+b_2+\cdots+b_{2n})$ (where $g(\cdot)$ is the function being minimized in(2.12)) with respect to $a_1,\dots,a_\mu,b_1,\dots,b_{2n}$ at the point $(\overline{a}_1,\dots\overline{a}_\mu,\overline{b}_1,\dots,\overline{b}_{2n})$ are equal to zero. This leads to the relations

$$\int_{\mathbb{T}}\varphi_j(t)\big(Q_p\overline{x}\big)(t)dt=0,\quad j=1,\dots,\mu, \tag{2.13}$$

$$\int_{\mathbb{T}}z_i(t)\big(Q_p\overline{x}\big)(t)dt=\frac{\alpha^p}{2n}Q_p\overline{b}_i,\quad i=1,\dots,2n, \tag{2.14}$$

where $\overline{x}(\cdot)=\sum_{j=1}^{\mu}\overline{a}_j\varphi_j(t)+\sum_{i=1}^{2n}\overline{b}_iz_i(\cdot)$.

We remark that $g(a_1,\dots,a_\mu,b_1,\dots,b_{2n})=g(da_1,\dots,da_\mu,db_1,\dots,db_{2n})$ for any $d\neq 0$, and hence the vector $(d\,\overline{a}_1,\dots,d\,\overline{a}_\mu,d\,\overline{b}_1,\dots,d\,\overline{b}_{2n})$ is also a solution of (2.12). Thus, it can be assumed that $|\overline{b}_i|\le 1,\ i=1,\dots,2n$, and $\overline{b}_{i_0}=(-1)^{i_0+1}$ for some $i_0,\ 1\le i_0\le 2n$.

Let

$$\widetilde{x}_{2n}(t)=\sum_{j=1}^{\mu}a_j^\star\varphi_j(t)+\sum_{i=1}^{2n}(-1)^{i+1}z_i(t), \tag{2.15}$$

and $\widetilde{x}_{2n}$ satisfies (1.7). Let $a^\star=(a_1^\star,\dots,a_{2n}^\star)$ and $b^\star=(1,-1,\dots,1,-1)\in\mathbb{R}^{2n}$. It follows from the definitions of $\widetilde{x}_{2n}(\cdot)$ and $\overline{x}(\cdot)$ that

$$\mathcal{L}_r(D)\widetilde{x}_{2n}(t)-\mathcal{L}_r(D)\overline{x}(t)=\sum_{\substack{i=1\\ i\neq i_0}}^{2n}\big((-1)^{i+1}-\overline{b}_i\big)\chi_i(t)\mathcal{L}_r(D)x_{2n}\left(t-\frac{(i-1)\pi}{n}\right), \tag{2.16}$$

and hence $S_c(\mathcal{L}_r(D)\widetilde{x}_{2n}(\cdot),\mathcal{L}_r(D)\overline{x}(\cdot))$ has at most $2n-2$ sign changes. Then, by Rolle's theorem, $S_c(\mathcal{L}_r(D)\widetilde{x}_{2n}(\cdot)-\mathcal{L}_r(D)\overline{x}(\cdot))\le 2n-2$. For any $a,b\in\mathbb{R}$, $\operatorname{sign}(a+b)=\operatorname{sign}(Q_pa+Q_pb)$, therefore

$$S_c\big(\big(Q_p\widetilde{x}_{2n}\big)(\cdot)-\big(Q_p\overline{x}\big)(\cdot)\big)\le 2n-2. \tag{2.17}$$

In addition, since $\widetilde{x}_{2n}$ is 2π-periodic solution of the linear differential equation $\mathcal{L}_r(D)y(t)=(-1)^r\lambda^{-p}(Q_px)(t)$, and $\varphi_j(t)\in\operatorname{Ker}\mathcal{L}_r(D)$. Then, by [7, page 94], we have

$$\int_{\mathbb{T}}\varphi_j(t)\big(Q_p\widetilde{x}\big)(t)dt=0,\quad j=1,\dots,\mu. \tag{2.18}$$

If we now multiply both sides of (2.15) by $(Q_p\widetilde{x}_{2n})(t)$, and integrate over the interval $\Delta_i,\ 1\le i\le 2n$, we get

$$\int_{\Delta_i}z_i(t)\big(Q_p\widetilde{x}_{2n}\big)(t)dt=(-1)^{i+1}\int_{\Delta_i}|\widetilde{x}_{2n}(t)|^pdt=(-1)^{i+1}\frac{\lambda_{2n}^p}{2n}. \tag{2.19}$$

Due to $\int_{\mathbb{T}}z_i(t)\big(Q_p\widetilde{x}_{2n}\big)(t)dt=\int_{\Delta_i}z_i(t)\big(Q_p\widetilde{x}_{2n}\big)(t)dt$. Therefore, we have

$$\int_{\mathbb{T}}z_i(t)\big(Q_p\widetilde{x}_{2n}\big)(t)dt=(-1)^{i+1}\frac{\lambda_{2n}^p}{2n},\quad i=1,\dots,2n. \tag{2.20}$$

Changing the order of integration and using (2.14) and (2.20), we get that

$$\int_{\Delta_i} \mathcal{L}_r(D)x_{2n}\left(t-\frac{(i-1)\pi}{n}\right)\left(\frac{1}{\pi}\int_{\mathbb{T}} G_r(t-\tau)\left((Q_p\widetilde{x}_{2n})(\tau)-(Q_p\overline{x})(\tau)\right)d\tau\right)dt$$
$$=\int_{\mathbb{T}} z_i(t)\left((Q_p\widetilde{x}_{2n})(t)-(Q_p\overline{x})(t)\right)dt=\frac{1}{2n}\left((-1)^{i+1}\lambda_{2n}^p-\alpha^p Q_p\overline{b}_i\right). \tag{2.21}$$

Denote by $f(\cdot)$ the factor multiply $\mathcal{L}_r(D)x_{2n}(t-(i-1)\pi/n)$ in the integral in the left-hand side of this equality. If we assume that $\lambda_{2n}>\alpha$, then we arrive at the relations

$$\operatorname{sign}\int_{\Delta_i} \mathcal{L}_r(D)x_{2n}\left(t-\frac{(i-1)\pi}{n}\right)f(\cdot)dt=(-1)^{i+1},\quad i=1,\dots,2n. \tag{2.22}$$

Suppose for definiteness that $\mathcal{L}_r(D)x_{2n}(t-(i-1)\pi/n)>0$ interior to Δ_i, $i=1,\dots,2n$. Then it follows from (2.22) that there are points $t_i\in\Delta_i$ such that $\operatorname{sign} f(t_i)=(-1)^{i+1}$, $i=1,\dots,2n$, that is, $S_c(f(\cdot))\geq 2n-1$. But $f(\cdot)$ is periodic, and hence $S_c(f(\cdot))\geq 2n$, therefore, $S_c(\mathcal{L}_r(D)f(\cdot))\geq 2n$. Further, $\mathcal{L}_r(D)f(\cdot)=(Q_p\widetilde{x}_{2n})(t)-(Q_p\overline{x})(t)$, that is, $S_c((Q_p\widetilde{x}_{2n})(t)-(Q_p\overline{x})(t))\geq 2n$.

We have arrived at a contradiction to (2.17), and hence $\lambda_{2n}\leq\alpha$. Thus $b_{2n-1}(W_p(\mathcal{L}_r);L^p)\geq\lambda_{2n}$.

2.2. *Upper estimate of Bernstein n-width*

Assume the contrary: $b_{2n-1}(W_p(\mathcal{L}_r);L^p)>\lambda_{2n}$, $(1<p<\infty)$. Then, by definition, there exists a linearly independent system of $2n$ functions $L_{2n}:=\operatorname{span}\{f_1,\dots,f_{2n}\}\subset L^p$ and number $\gamma>\lambda_{2n}$ such that $L_{2n}\cap\gamma S(L^p)\subseteq\mathcal{L}_r(D)$, or equivalently,

$$\min_{x(\cdot)\in L_{2n}}\frac{\|x(\cdot)\|_p}{\|\mathcal{L}_r(D)x(\cdot)\|_p}\geq\gamma>\lambda_{2n}. \tag{2.23}$$

Let us assign a vector $c\in\mathbb{R}^{2n}$ to each function $x(\cdot)\in L_{2n}$ by the following rule:

$$x(\cdot)\longrightarrow c=(c_1,\dots,c_{2n})\in\mathbb{R}^{2n},\quad \text{where } x(\cdot)=\sum_{j=1}^{2n}c_jf_j(\cdot). \tag{2.24}$$

Then (2.23) acquires the form

$$\min_{c\in\mathbb{R}^{2n}\setminus\{0\}}\frac{\|\sum_{j=1}^{2n}c_jf_j(\cdot)\|_p}{\|\sum_{j=1}^{2n}c_j\mathcal{L}_r(D)f_j(\cdot)\|_p}\geq\gamma>\lambda_{2n}. \tag{2.25}$$

Let $c_0=0$. Consider the sphere S^{2n-1} in the space $\mathbb{R}^{2n}$ with radius 2π, that is,

$$S^{2n-1}:=\left\{c: c=(c_1,\dots,c_{2n})\in\mathbb{R}^{2n},\ \|c\|=\sum_{j=1}^{2n}|c_j|=2\pi\right\}. \tag{2.26}$$

To every vector $c \in \mathbb{R}^{2n}$ we assign function $u(t,c)$ defined by

$$u(t,c) = \begin{cases} (2\pi)^{-1/p} \operatorname{sign} c_j, & \text{for } t \in (t_{k-1}, t_k),\ k = 1,\ldots,2n, \\ 0, & \text{for } t = t_k,\ k = 1,\ldots,2n-1, \end{cases} \tag{2.27}$$

where $t_0 = 0, t_k = \sum_{i=1}^{k} |c_i|,\ k = 1,\ldots,2n$, and the extended 2π-periodically onto $\mathbb{R}$.

An analog of the Buslaev iteration process [8] is constructed in the following way: the function $x(t,c)$ is found as a periodic solution of the linear differential equation $\mathcal{L}_r(D)x_0 = u$, then the periodic functions $\{x_k(t,c)\}_{k\in\mathbb{N}^+}$ are successively determined from the differential equations

$$\begin{aligned} \mathcal{L}_r(D)x_k(t) &= (Q_{p'} y_k)(t), \\ \mathcal{L}_r(D)y_k(t) &= (-1)^r \mu_{k-1}^{-p} (Q_{p'} x_{k-1})(t), \end{aligned} \tag{2.28}$$

where $p' = p/(p-1)$, and the constants $\{\mu_k : k = 0,\ldots,\}$ are uniquely determined by the conditions

$$\|\mathcal{L}_r(D)x_k\|_p = 1, \qquad (Q_p x_k)(t) \perp \operatorname{Ker}\mathcal{L}_r(D), \qquad (Q_{p'} y_k)(t) \perp \operatorname{Ker}\mathcal{L}_r(D). \tag{2.29}$$

By analogy with the reasoning in [8], we can prove the following assertions:

(i) the iteration procedure (2.28)-(2.29) is well de fined, the sequences $\{\mu_k\}_{k\in\mathbb{N}}$ is monotone nondecreasing and converge to an eigenvalue $\lambda(c) > 0$ of the problem (1.7),

(ii) the sequence $\{x_k(\cdot,c)\}_{k\in\mathbb{N}}$ has a subsequence that is convergent to an eigenfunction $x(\cdot,c)$ of the problem (1.7), with $\lambda(c) = \|x(\cdot,c)\|_p$,

(iii) for any $k \in \mathbb{N}$ there exists a $\widehat{c} \in S^{2n-1}$ such that $x_k(\cdot,\widehat{c})$ has at least $2n$ zeros $(Z_c(x_k(\cdot,\widehat{c})) \geq 2n)$ on $\mathbb{T}$,

(iv) in the set of spectral pairs $(\lambda(c), x(\cdot,c))$, there exists a pair $(\lambda(\widehat{c}), x(\cdot,\widehat{c}))$ such that $S_c(x(\cdot,\widehat{c}) = 2N \geq 2n$.

Items (i) and (ii) can be proved in the same way as [8, Sections 6 and 10]. Item (iii) follows from the Borsuk theorem [9], which states that there exists a $\widehat{c} \in S^{2n-1}$ such that $Z_c(x_k(\cdot,\widehat{c})) \geq 2n-1$, but since the function $x_k(\cdot,\widehat{c})$ is periodic, we actually have $Z_c(x_k(\cdot,\widehat{c})) \geq 2n$. Finally, item (iv), by (ii) and (iii), which $Z_c(x(\cdot,\widehat{c})) \geq 2n$. In view of $x(\cdot,\widehat{c})$ zeros are simple, therefore, $S_c(x(\cdot,\widehat{c})) \geq 2n$.

Since spectral pairs of (1.7) are unique and the Kolmogorov width $d_{2n}(W_p(\mathcal{L}_r); L^q) = \lambda_{2n}(p,q,\mathcal{L}_r)$ for $p \geq q$ [5], when $n \geq N$, it follows that

$$\lambda(\widehat{c}) = \lambda_{2N} = d_{2N}(W_p(\mathcal{L}_r); L^p) \leq d_{2n}(W_p(\mathcal{L}_r); L^p) = \lambda_{2n}. \tag{2.30}$$

Therefore, by virtue of items (i), (ii), and (2.30), we obtain

$$\min_{c\in\mathbb{R}^{2n}\setminus\{0\}} \frac{\|\sum_{j=1}^{2n} c_j f_j(\cdot)\|_p}{\|\sum_{j=1}^{2n} c_j \mathcal{L}_r(D) f_j(\cdot)\|_p} \leq \frac{\|\sum_{j=1}^{2n} \widehat{c}_j f_j(\cdot)\|_p}{\|\sum_{j=1}^{2n} \widehat{c}_j \mathcal{L}_r(D) f_j(\cdot)\|_p} \leq \frac{\|x_k(\cdot,\widehat{c})\|_p}{\|\mathcal{L}_r(D)x_k(\cdot,\widehat{c})\|_p} \leq \lambda(\widehat{c}) = \lambda_{2N} \leq \lambda_{2n}, \tag{2.31}$$

which contradicts (2.25). Hence $b_{2n-1}(W_p(\mathcal{L}_r); L^p) \leq \lambda_{2n}$. Thus, the upper bound is proved. This completes the proof of the theorem.

Acknowledgments

Project was supported by the Natural Science Foundation of China (Grant no. 10671019) and Scientific Research Fund of Zhejiang Provincial Education Department (Grant no. 20070509).

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