

NORTH-HOLLAND MATHEMATICS STUDIES  
Notas de Matemática (101)

111

Editor: Leopoldo Nachbin

## RECENT PROGRESS IN FOURIER ANALYSIS

*Proceedings of the Seminar on Fourier Analysis held in  
El Escorial, Spain, June 30 - July 5, 1983*

*Edited by*

I. PERAL and J.-L. RUBIO de FRANCIA

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**I. PERAL and J.-L. RUBIO de FRANCIA**

*Universidad Autónoma de Madrid  
Madrid  
Spain*



1985

NORTH-HOLLAND - AMSTERDAM • NEW YORK • OXFORD

• Elsevier Science Publishers B.V., 1985

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ISBN: 0 444 87745 2

*Publishers:*

ELSEVIER SCIENCE PUBLISHERS B.V.  
P.O. Box 1991  
1000 BZ Amsterdam  
The Netherlands

*Sole distributors for the U.S.A. and Canada:*

ELSEVIER SCIENCE PUBLISHING COMPANY, INC.  
52 Vanderbilt Avenue  
New York, N.Y. 10017  
U.S.A.

**Library of Congress Cataloging in Publication Data**

Seminar on Fourier Analysis (1983 : Escorial) ;  
Recent progress in Fourier analysis.

(North-Holland mathematics studies ; 111) (Notas de  
matemática ; 101)

English or French.

I. Fourier analysis--Congresses. I. Peral, Ireneo.  
II. Rubio de Francia, J.-L., 1949- . III. Title.  
IV. Series. V. Series: Notas de matemática (Rio de  
Janeiro, Brazil) ; no. 101.

QA1.N86 no. 101a 510 s [515'.2433] 85-4531

QA403.51

ISBN 0-444-87745-2 (Elsevier Science Pub.)

PRINTED IN THE NETHERLANDS

## RECENT PROGRESS IN FOURIER ANALYSIS

*The following contributions were presented at the Seminar on Fourier Analysis which was held in El Escorial from 30 June to 5 July 1983. This meeting was sponsored by the Asociación Matemática Española with financial support from the Comisión Asesora de Investigación Científica y Técnica (project 4192).*

*A decisive factor with respect to the organization was the financial help, together with the facilities, provided by the Vicerrectorado de Investigación of the Universidad Autónoma de Madrid.*

*The articles we present give a good idea of how work in the area has evolved and of the scientific character of the meeting. The friendly and cordial atmosphere meant that the organization, far from being a chore, became a pleasurable experience. For this we owe our sincerest thanks to all participants.*

*Special thanks must also go to the invited speakers for their magnificent collaboration, and to Caroline, without whose presence we hate to think what could have happened!*

*We should also like to express our gratitude to our colleagues in the División de Matemáticas in the Universidad Autónoma de Madrid, for their help in correcting proofs, and to Soledad, for typing the manuscript.*

*The Editors*

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## FUNCTIONS OF $L^p$ -BOUNDED PSEUDO-DIFFERENTIAL OPERATORS

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The aim of this paper is to construct a functional calculus over an algebra of  $L^p$ -bounded pseudo-differential operators acting on functions defined on a compact manifold without boundary.

The operators we consider here depend on amplitudes or symbols with a finite number of derivatives, without any hypothesis of homogeneity. The manifolds where the operators act are also of class  $C^M$  for a suitable  $M$ . In this way is it possible to control the number of derivatives of  $f$  that we need in order to give meaning to  $f(A)$ , when  $A$  is a self-adjoint operator in that algebra.

Indeed, this program was carried out in [1] and [2] when  $p = 2$ . In [1] an algebra of pseudo-differential operators acting on functions defined in  $\mathbb{R}^n$  is constructed. The main tool to do that is the sharp  $L^2$  estimates obtained by R. Coifman and Y. Meyer in [3]. Then, functions of those operators are defined by means of the H. Weyl formula (see [4], for example). Since it seems not to be possible to obtain directly a polynomial estimate for the exponential  $\exp(-2\pi itA)$  in terms of  $t$ , a roundabout argument is employed by introducing an adapted version of the characteristic operators defined by A. P. Calderón in [5].

All this machinery is extended in [2] to non-infinitely differentiable compact manifolds without boundary.

In order to get the  $L^p$  version of these results the first thing to do is to obtain the analogous of the algebra constructed in [1]. The main point is to observe that amplitudes in a subclass of  $S_{1,1}^0$  give rise to operators on which the classical theory of Calderón and Zygmund works (see [6]). Unfortunately as far as I know, it is an open question to get in the euclidean case a non trivial estimate for the exponential  $\exp(-2\pi itA)$ . However, when the operators act on

functions defined in compact manifolds, a suitable estimate can be obtained and so, a non-infinitely differentiable functional calculus runs.

Given  $0 \leq \delta < 1$ ,  $k = 1, 2, \dots$ , let

$$N = \begin{cases} k/1-\delta & \text{if this is an integer} \\ [k/1-\delta] + 1 & \text{if not} \end{cases}$$

We will consider operators  $K$  acting on  $S$  in the following way

$$Kf = \sum_{j=0}^{N-1} \int e^{-2\pi i x \xi} p_j(x, \xi) \hat{f}(\xi) d\xi + Rf$$

where

i) The function  $p_j$  belongs to the class  $S^j$ ; that is to say,  $p_j$  is a continuous function defined on  $\mathbb{R}^n \times \mathbb{R}^n$ ; it has continuous derivatives in the variable  $\xi$  up to the order  $n+N+2-j$  and each function  $D_\xi^\gamma p_j$  has continuous derivatives in  $x, \xi$  up to the order  $2[n/2]+N+k+2-j$ , satisfying

$$\sup_{\substack{x, \xi \in \mathbb{R}^n \\ \alpha, \beta, \gamma}} \frac{|D_s^\alpha D_\xi^\beta D_\xi^\gamma p_j(x, \xi)|}{(1+|\xi|)^{-j}(1-\delta)+|\alpha|\delta-|\beta+\gamma|} < \infty$$

ii) For  $1 < p_0 \leq 2$  fixed,  $R$  is a linear and continuous operator from  $L^p$  into itself for  $p_0 \leq p \leq p'_0$ . Moreover,  $R$  and the adjoint  $R^*$  are continuous from  $L^p$  into  $L^p_k$ , where  $L^p_k$  denotes the Sobolev space of order  $k$  and  $p'_0$  is the conjugate exponent of  $p_0$ .

Let  $M_k$  be the class of the operators  $K$ .

Now, let  $X$  be a differentiable compact manifold of dimension  $n$  and class  $C^M$ ,  $M = 2[n/2]+n+2N+k+5$ , without boundary;  $X$  has a measure  $\mu$  which in terms of any local coordinate system  $x = (x_1, \dots, x_n)$  can be express as  $G(x)dx_1 \dots dx_n$ , where  $G > 0$  is a function of class  $C^{M-1}$ .

We will introduce the following notation.

Let  $U_1, U_2$  be open bounded subsets of  $X$  or  $\mathbb{R}^n$  let  $\phi : U_1 \rightarrow U_2$  be a diffeomorphism of class  $C^M$ ; if  $f$  is a function defined on the ambient space of  $U_2$ ,  $\phi^*(f)$  will denote the function



defined on the ambient space of  $U_1$  which coincides with  $f \circ \phi$  on  $U_1$  and vanishes outside  $U_1$ . On the other hand, if  $A$  is an operator acting on functions defined on the ambient space of  $U_2$ , by  $\phi^*(A)$  we denote the operator acting on functions defined on the ambient space of  $U_1$  as

$$\phi^*(A)(f) = \phi^*[A(\phi^{-1*}(f))]$$

Now, we are ready to define classes of operators on  $X$ .

Given  $1 < p_0 \leq 2$ ,  $R$  belongs to  $R_k(X)$  if  $R$  is a linear continuous operator from  $L^p(X)$  into itself for  $p_0 \leq p \leq p'_0$  and  $R, R^*$  map continuously  $L^p(X)$  into  $L^p_k(X)$  for  $p_0 \leq p \leq p'_0$ .

$R_k(X)$  is a self-adjoint Banach algebra with the norm

$$|R|_{R_k} = |R|_{L^{p_0}, L^{p_0}} + |R|_{L^{p'_0}, L^{p'_0}} + |R^*|_{L^{p_0}, L^{p_0}} + |R^*|_{L^{p'_0}, L^{p'_0}}$$

Now, given  $1 < p_0 \leq 2$ ,  $M_k(X)$  is the class of linear continuous operators  $A$  from  $L^p(X)$  into itself for  $p_0 \leq p \leq p'_0$ , which satisfy the following two conditions

i) Given  $\phi_1, \phi_2 \in C_0^M(X)$  with disjoint supports, the operator  $\phi_1 A \phi_2$  belongs to  $R_k(X)$ . Here  $\phi_1, \phi_2$  stand for the operators of multiplication by the function  $\phi_1, \phi_2$ , respectively.

ii) Let  $U \subset X$  be an open subset and let  $\phi : U \rightarrow U_1$  be a diffeomorphism of class  $C^M$  extendable to a neighborhood of  $\bar{U}$ , where  $U_1 \subset \mathbb{R}^n$ . There exists an operator  $A_1 \in M_k$  such that if  $\phi_1, \phi_2 \in C_0^M(U)$ ,

$$\phi_1 A \phi_2 = \phi_1 \phi^*(A_1) \phi_2$$

$M_k(X)$  is a self-adjoint algebra and  $R_k(X)$  is a two-sided ideal of  $M_k(X)$ ; moreover, operators in  $M_k(X)$  are continuous from  $L^p_m(X)$  into itself for  $p_0 \leq p \leq p'_0$ ,  $0 \leq m \leq k$ .

It is possible to endow  $M_k(X)$  with a complete norm. In order to avoid technical details, we will not precise the definition. With this norm  $R_k(X)$  is continuously included in  $M_k(X)$  and  $M_k(X)$  is continuously included in  $L(L^p_m(X))$ , the space of linear and continuous operators from  $L^p_m(X)$  into itself, for  $p_0 \leq p \leq p'_0$ ,  $0 \leq m \leq k$ .

THEOREM 1. Let  $p_0$ ,  $k$  and  $n$  be such that  $1/p_0 - k/n \leq 1/2$ .

Given a self-adjoint operator  $A \in M_k(X)$  and a function  $f$  in the Sobolev space  $L^2_s$ , where  $s > 2\mu + 5/2$ ,  $\mu = 2[n/2] + n + k + N(N+3)/2 + 4$ , the Bochner integral

$$\int_{-\infty}^{\infty} e^{-\pi i t A} \hat{f}(t) dt$$

belongs to  $R_k(X)$  and coincides with  $f(A)$  calculated by means of the spectral formula in  $L(L^2(X))$ .

Remarks:

- a) It is possible to impose on  $f$  additional conditions under which the operator  $f(A)$  belongs to  $R_k(X)$ .
- b) When  $p_0 = 2$  the above theorem remains true with  $s > \mu + 3/2$ .
- c) The Weyl's formula also allows to define functions of a tuple of non-commuting self-adjoint operators.

We will include here the proof of the theorem 1 in a particular but significant case.

Suppose that  $\delta = 0$ ,  $k = 1$ ; it follows that  $N = 1$ . It is clear that theorem 1 can be deduced from a suitable estimate for  $|\exp(-2\pi i t A)|_{M_1(X)}$  in terms of  $t \in \mathbb{R}$ .

In order to get this estimate, some notations and results will be needed. We fix in  $X$  coordinate neighborhoods  $U_j$ , diffeomorphisms  $\phi_j : U_j \rightarrow \phi_j(U_j)$  of class  $C^M$ , where  $M = 2[n/2] + n + 8$ , functions  $\theta_j \in C^M_0(U_j)$ ,  $\theta_j \geq 0$  and a finite partition of unity  $\{\eta_j\}$  of class  $C^M$ , such that  $\text{supp}(\theta_j) \subset U_i$  whenever  $\text{supp}(\theta_j) \cap \text{supp}(\theta_i) \neq \emptyset$ ;  $\theta_i = 1$  in a neighborhood of  $\text{supp}(\eta_j)$  if  $j = i$  or if  $\text{supp}(\eta_j) \cap \text{supp}(\eta_i) \neq \emptyset$ .

Now, we define an space of symbols for operators in  $M_1(X)$ . More exactly, for each  $j$  we consider the restriction to  $\phi_j(U_j)$  of a function  $p^{(j)} \in S^0$ . We define a norm of such a restriction as

$$|p^{(j)}| = \sup \frac{|D_x^\alpha D_\xi^\beta p^{(j)}(x, \xi)|}{(1 + |\xi|)^{-|\gamma + \beta|}}$$

where the supremum is taken over  $x \in \phi_j(U_j)$ ,  $\xi \in \mathbb{R}^n$ ,  $|\xi| \leq n+3$ ,

$$|\alpha + \beta| \leq 2[n/2] + 4, j.$$

We note  $\mathbb{M}_1(X)$  this space. With the pointwise multiplication

$$(p^{(j)}) \cdot (q^{(j)}) = (p^{(j)} q^{(j)})$$

as a product,  $\mathbb{M}_1(X)$  becomes a commutative Banach algebra.

LEMMA. Let  $H = (p^{(j)})$  be an element in  $\mathbb{M}_1(X)$ ; we suppose that each  $p^{(j)}$  is a real function. Then, if  $t \in \mathbb{R}$ ,

$$|\exp(-2\pi i t H)| \leq C(1 + |H|)(1 + |t|)^\mu$$

where  $C = C(X) > 0$ ,  $\mu = 2[n/2] + n + 7$ .

#### Proof

Since  $\mathbb{M}_1(X)$  is a Banach algebra, the exponential  $\exp(-2\pi i t H)$  is well defined; moreover it is equal to  $\exp(-2\pi i t p^{(j)})_j$ . According to the norm that the space  $\mathbb{M}_1(X)$  has, the conclusion follows.

Now, we will introduce the space  $\mathbb{M}_1(X)$  in the following way. An element  $K$  of  $\mathbb{M}_1(X)$  is an operator  $R$  in  $\mathcal{R}_1(X)$  and a vector  $(p^{(j)})$  in  $\mathbb{M}_1(X)$  subject to the condition that if  $U_i \cap U_j \neq \emptyset$  and  $\phi_{ij} = \phi_j \circ \phi_i^{-1}$ , then

$$(p^{(i)}) = \phi_{ij}^* (p^{(j)}) \quad \text{in} \quad \phi_i(U_i \cap U_j).$$

Such an element  $K$  will be denoted as  $\{(p^{(j)}), R\}$ .

We define a norm in  $\mathbb{M}_1(X)$  as follows

$$|K|_{\mathbb{M}_1} = |(p^{(j)})| + |R|_{\mathcal{R}_1}$$

Given  $K \in \mathbb{M}_1(X)$  we define an operator  $\Lambda(K)$  in the following way

$$\Lambda(K) = \sum_j \eta_j \phi_j^* (A_j) \theta_j + R$$

where

$$(A_j f)(x) = \begin{cases} \int e^{-2\pi i x \xi} p^{(j)}(x, \xi) \hat{f}(\xi) d\xi & \text{if } x \in \phi_j(U_j) \\ 0 & \text{if not} \end{cases}$$

It can be proved that  $\Lambda(K)$  belongs to  $M_1(X)$ . Moreover, the linear map

$$\begin{array}{ccc} M_1(X) & \xrightarrow{\Lambda} & M_1(X) \\ K & \longrightarrow & \Lambda(K) \end{array}$$

is into and continuous. Furthermore, if  $A \in M_1(X)$  is self-adjoint,  $A = \Lambda(K)$  for some  $K = \{(p^{(j)}), R\}$ , with  $p^{(j)}$  real for all  $j$ .

It is possible to define a product in  $M_1(X)$  in such a way that  $M_1(X)$  becomes a Banach algebra and the map  $\Lambda$  above is a continuous homomorphism of algebras.

Finally, let us consider the maps

$$\begin{array}{ccccc} M_1(X) & \xrightarrow{\Omega} & M_1(X) & \xrightarrow{\Omega_1} & M_1(X) \\ \{(p^{(j)}), R\} & \longrightarrow & (p^{(j)}) & \longrightarrow & \{(p^{(j)}), 0\} \end{array}$$

$\Omega$  is a continuous homomorphism of algebras and the linear map  $\Omega_1$  is a right continuous inverse of  $\Omega$ .

**THEOREM 2.** Suppose that  $1/p_0 - 1/n \leq 1/2$ .

Let  $H = \{(p^{(j)}), R\}$  be an element of  $M_1(X)$  such that  $\Lambda(H)$  is a self-adjoint operator and the functions  $p^{(j)}$  are real for all  $j$ . Then, if  $t \in \mathbb{R}$ ,

$$|\exp(-2\pi i t H)|_{M_1} \leq C[(1 + |H|_{M_1})(1 + |t|)]^{2\mu+2}$$

where  $C = C(X) > 0$ ,  $\mu = 2[n/2] + n + 7$ .

### Proof

According to the notations above, we set  $A = \Lambda(H)$ ,  $K = \Omega(H) = (p^{(j)}) \in M_1(X)$ .

We assert that

$$e^{-2\pi i t H} - \Omega_1(e^{-2\pi i t K})$$

is an element of the form  $\{(0), R(t)\}$ .

In fact, since  $\Omega$  is a continuous homomorphism of algebras and  $\Omega_1$  is a right inverse of  $\Omega$ , we have

$$\Omega[e^{-2\pi i t H} - \Omega_1(e^{-2\pi i t K})] = e^{-2\pi i t K} - \Omega\Omega_1(e^{-2\pi i t K}) = 0.$$

On the other hand, since  $\Omega_1$  is a continuous map, according to the lemma it suffices to estimate the norm of  $\{(0), R(t)\}$  in  $IM_1(X)$ , which coincides with the norm of  $R(t)$  in  $R_1(X)$ .

We have

$$\begin{aligned} R(t) &= \Lambda[e^{-2\pi i t H} - \Omega_1(e^{-2\pi i t K})] = \\ &= e^{-2\pi i t A} - \Lambda\Omega_1(e^{-2\pi i t K}). \end{aligned}$$

If we denote with  $\dot{R}(t)$  the derivative of  $R(t)$  with respect to  $t$ , we get

$$\begin{aligned} \dot{R}(t) &= e^{-2\pi i t A}(-2\pi i A) - \Lambda\Omega_1(e^{-2\pi i t K}(-2\pi i K)) = \\ &= [e^{-2\pi i t A} - \Lambda\Omega_1(e^{-2\pi i t K})](-2\pi i A) + \Lambda\Omega_1(e^{-2\pi i t K})(-2\pi i A) - \\ &- \Lambda\Omega_1(e^{-2\pi i t K})(-2\pi i K) = R(t)(-2\pi i A) + B_1(t) \end{aligned} \quad (1)$$

Since

$$B_1(t) = \Lambda[\Omega_1(e^{-2\pi i t K})(-2\pi i H) - \Omega_1(e^{-2\pi i t K})(-2\pi i K)]$$

and

$$\Omega[\Omega_1(e^{-2\pi i t K})(-2\pi i H) - \Omega_1(e^{-2\pi i t K})(-2\pi i K)] = 0,$$

we deduce that  $B_1(t)$  belongs to  $R_1(X)$  for each  $t$ .

Thus,

$$\begin{aligned} |B_1(t)|_{R_1} &= |\Omega_1(e^{-2\pi i t K})(-2\pi i H) - \Omega_1(e^{-2\pi i t K})(-2\pi i K)|_{IM_1} \\ &\leq C[(1 + \|H\|_{IM_1})(1 + |t|)]^\mu \end{aligned}$$

where  $C = C(X) > 0$ .

Since  $R(0) = 0$ , from (1) it follows that

$$R(t) = \int_0^t B_1(s) e^{-2\pi i(t-s)A} ds \quad (2)$$

But we can also write

$$R(t) = (-2\pi i A) e^{-2\pi i t A} - \Lambda\Omega_1(e^{-2\pi i t K})(-2\pi i K)$$

or

$$R(t) = (-2\pi i A) R(t) + B_2(t)$$

where  $B_2(t) \in R_1(X)$  for each  $t$  and

$$|B_2(t)|_1 \leq C[(1 + |H|_{M_1})(1 + |t|)]^\mu, \quad c = C(X) > 0$$

So,

$$R(t) = \int_0^t e^{-2\pi i(t-s)A} B_2(s) ds \quad (3)$$

or

$$R^*(t) = \int_0^t B_2^*(s) e^{2\pi i(t-s)A} ds \quad (4)$$

where  $*$  denotes the adjoint.

Now, suppose we show that

$$|e^{-2\pi i(t-s)A}|_{L^{p_0}, L^p} \leq C[(1 + |H|_{M_1})(1 + |t-s|)]^{\mu+1} \quad (5)$$

We will get the same estimate for

$$|e^{-2\pi i(t-s)A}|_{L^{p'_0}, L^{p'_0}}$$

Thus, according to (2) and (4), we can deduce that

$$|R(t)|_{R_1} \leq C[(1 + |H|_{M_1})(1 + |t|)]^{2\mu+2}$$

So, it remains to prove (5).

From the definition of the operator  $R(t)$ , it is clear that it suffices to obtain the estimate

$$|R(t)|_{L^{p_0}, L^{p_0}} \leq C[(1 + |H|_{M_1})(1 + |t|)]^{\mu+1}$$

But according to the hypothesis  $1/p_0 - 1/n \leq 1/2$ , the Sobolev immersion theorem provides the continuous inclusion of  $L_1^{p_0}(X)$  into  $L^2(X)$ ; moreover, since  $p_0 \leq 2$ , we also have a continuous injection from  $L^2(X)$  into  $L^{p_0}(X)$ . Thus, the desired estimate follows from (3).

This completes the proof of the theorem 2.

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# ON PROBLEMS RELATED TO THEOREMS A and B WITH ESTIMATES

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## Introduction

We are interested in theorems of type Cartan A and B, but with estimates on the growth of the functions.

## Type A problems

a) The characterisation of the zero set of a holomorphic function in a given class. G. Henkin and H. Skoda gave, independently, a complete answer for this problem in the case of the Nevanlinna class of the unit ball  $B$  of  $\mathbb{C}^n$ , [12], [18]; N. Varopoulos studied the case of the Hardy classes  $H^p$  of the unit ball [19].

All of them used the P. Lelong's method leading to solve a  $\partial\bar{\partial}$  equation with estimates.

b) Another example of type A problem is the corona problem:  
 let  $f_1, \dots, f_k$  be bounded holomorphic functions in the unit ball of  $\mathbb{C}^n$  such that:

$$|f_1| + \dots + |f_k| \geq \delta > 0 \text{ in } B;$$

are there  $g_1, \dots, g_k$  bounded holomorphic functions in  $B$  with:  
 $f_1 g_1 + \dots + f_k g_k = 1$ ?

This problem was solved in 1962 by L. Carleson [9] in the case  $n = 1$ ; L. Hormander [14] showed that the problem can be replaced by the problem of solving a  $\bar{\partial}$  equation with bounded solution, and in 1979 T. Wolff gave a very simple proof of the Corona in one variable. We will show in §1, in generalizing the proof of Wolff to the unit ball of  $\mathbb{C}^n$ , that in fact it is a  $\partial\bar{\partial}$  equation we are led to solve. Unfortunately we have not the complete answer but the following:

Theorem [1]. Let  $f = (f_1, \dots, f_k)$ ,  $k$  functions in the Hardy class