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A NON-ORTHOGONAL FOURIER EXPANSION FOR CONIC DECOMPOSITION

by

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A NON-ORTHOGONAL FOURIER EXPANSION FOR CONIC DECOMPOSITION

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This research was partly supported by ONR Contract N00014-75-C-0569 with the Center for Cybernetic Studies, The University of Texas at Austin. Reproduction in whole or in part is permitted for any purpose of the United States Government.
The problem considered is that of constructing the decomposition of a vector in a Hilbert space into two orthogonal components; one (the "projection") in a given cone, and the other in the polar cone. The projection $Z^*$ can be expressed as a Fourier-type expansion. An algorithm for constructing this expansion is given, and shown to converge to $Z^*$.

Key Words: Conic decomposition, Optimization in Hilbert space, Projection on convex cone, Convex cone, Fourier series.
1. Introduction

A classical result in Hilbert space theory states that each element \( b \), of a Hilbert space \( H \), has a unique orthogonal decomposition with respect to a closed subspace \( M \subset H \), i.e., there exists a unique pair \((z^*, y^*)\) such that

\[
\begin{align*}
    b &= z^* + y^* \\
    z^* &\in M \\
    y^* &\in M^\perp
\end{align*}
\]

Moreover (e.g. Dunford and Schwartz [3]) the component \( y^* \) is the solution of the quadratic extremal problem

\[
||y^*||^2 = \min_{z \in M} ||b - z||^2.
\]

The so-called projection \( z^* \) of \( b \) onto \( M \), can be expanded as a Fourier sum

\[
z^* = \sum_{i=1}^{\infty} a_k e_k
\]

where \( \{e_k\} \) is an orthonormal basis of \( M \), and \( a_k \) is the Fourier coefficient \( a_k = (b, e_k) \). When \( M \) is given as

\[
M = \text{span} \{a_k : k=1, 2, \ldots\}
\]

with \( a_k \)'s not necessarily being orthogonal, the \( e_k \)'s in (1.3) are computed as

\[
e_k = \sum_{i=1}^{k} \lambda_i a_i
\]
where the coefficients $\lambda_i$ are determined by the Gram-Schmidt procedure.

Consider now the case where $M$ is replaced by a closed convex cone $C$. Here a pair $(z^*, y^*)$ is a conic decomposition with respect to $C$, if

\[
\begin{aligned}
&b = z^* + y^* \\
&z^* \in C \\
&y^* \in C^* \\
&(z^*, y^*) = 0
\end{aligned}
\]

(1.6)

where $C^*$ is the polar cone of $C$: $C^* = \{y \in H: (y, z) \leq 0, \forall z \in C\}$. Existence and uniqueness of such decomposition is shown by Moreau [8]. A representation of $y^*$ similar to (1.2) is

\[
| |y^*|^2 = \min_{z \in C} | |b - z|^2.
\]

(1.7)

Problem (1.7) is the classical minimum distance problem of optimization and approximation theory.

The fundamental role played in modern optimization theory by the subspace and cone decompositions, and their relations to the minimum distance problem, are well advocated in the books by Luenberger [5], Dorny [2] and Holmes [4], among others. In a finite dimensional space (1.7) is a quadratic programming problem, and the projection
y* can be computed by appropriate quadratic programming algorithms. The Cone Decomposition Theorem (existence and uniqueness) itself is a convenient analytical tool to treat topics such as: Theorems of the Alternatives, Duality in Linear Programming and more.

An interesting application of conic decomposition is discussed by Mackie [6], following the approach of Moreau. It illustrates nicely the use of modern concepts in optimization theory to the solution of a problem in particle and continuum mechanics. We outline the problem below and discuss it in more details in Section 6.

*Example 1.1*

A number of perfectly smooth, inelastic, identical, spherical ball-bearings fits exactly in the interior of a curved tube, whose radius of curvature is large compared with the radius of a ball, and are supported so that they are at rest in contact with one another with gravity acting vertically downwards. At time t=0 this support is removed and the balls begin to fall. The problem is to find the initial acceleration of each ball, and in particular to determine which balls initially remain in contact, and which tend to separate from each other.

For further applications see e.g. Moreau [8], Abeasis et al. [1] and Miersemann [7].
When $C$ is a closed convex set, the solution of the minimum distance problem (1.7) is attained uniquely. Thus the mapping $P_C(b)$ which associates with an element $b \in H$, its closest point in $C$, is a well defined function. Properties of these projection mappings were thoroughly investigated by Zarantonello [10], from the geometric and algebraic points of view. In particular it is shown, that the algebra of projections on convex cones retains, from the algebra of linear orthogonal projections, enough similar properties so as to develop a spectral theory, in the spirit of the spectral theory of linear selfadjoint operators.

The purpose of this paper is to furnish a Fourier type representation of the projection $Z^*$ in (1.7), similar to (1.3), (1.5), i.e.,

$$
\begin{align*}
Z^* &= \sum_{k=1}^{\infty} c_k d_k \\
d_k &= \sum_{i \in I_k} \mu_i a_i
\end{align*}
$$

(1.8)

Here

$$
C = \text{cone} \{a_i : i = 1, 2, \ldots\}
$$

(1.9)

is the closure of the set of all non-negative finite linear combinations of the $a_i$'s. The index set $I_k$ and the coefficient
\(\mu_i\) are determined by the CD Algorithm given in section 2.

The expression (1.8) is a generalization of (1.3), (1.5). Indeed, we show in section 5 that if the system \(\{a_i\}\) is orthonormal, then the non-zero terms in the expansion \(\sum_{k=1}^{\infty} c_k d_k\) are the same as those in \(\sum_{k=1}^{\infty} a_k a_k'\).

A representation of the projection \(z^*\) in terms of the original spanning set \(\{a_k\}\):

\[
(1.10) \quad z^* = \sum_{k=1}^{\infty} a_k a_k'
\]

is not guaranteed to converge even if \(C\) is a subspace. This is shown by the following (another example is given by Stakgold [9, p. 290]):

**Example 1.2**

In \(l_2\), the Hilbert space of sequences \(\{a_i\}_{i=1}^{\infty}\) such that \(\sum_{i=1}^{\infty} |a_i|^2 < \infty\), consider the sequence of vectors \(a_i\) defined component-wise by

\[
a_{ij} = \begin{cases} 1 & j = i \\ -1 & j = i + 1 \\ 0 & \text{otherwise}. \end{cases}
\]

Let \(b = (0, 1, 0, 0, ...),\) and \(M = \text{span} \{a_i\}\). Then \(z^* = b \in M\), but it is easily verified that there exists no representation of \(b\) in the form (1.10).

Since the original spanning set \(\{a_i\}\) is not adequate for such a representation, another set must be used. In the subspace
case this is the set of orthonormal vectors (1.5), while in the
conic case it is the set of $d_k$'s in (1.8), which generally are
not even linearly independent.

In spite of the above dissimilarity between the orthogonal
and conic expansions, the latter still retains important properties
(e.g. Bessel inequality) of the classical Fourier expansion.
These properties are obtained in sections 3 and 4.

2. **The Conic Decomposition Algorithm**

In this section we define an algorithm (abbreviated CD
Algorithm) for the construction of the expansion (1.8). We
assume with no loss of generality that the spanning vectors are
normalized: $|a_i| = 1$, $i = 1, 2, ...$

Let $N$ denote the positive integers, and define $\phi : N \to N$ as
the function which associates with $n \in N$ the index of the first
non-zero digit in the binary expansion of $n$, e.g., $\phi(2) = 2,$
$\phi(3) = 1.$

The CD Algorithm: At the $k$-th iteration, $k = 1, 2, ...$
one is given vectors $z_k, y_k$ in $H$, and scalars $(x_i^k)_{i=1}^\infty$, where
initially, $(k=1)$

$$z_1 = 0$$

$$(2.1) \quad y_1 = b$$

$$x_i^1 = 0 \quad \forall i \in N.$$ 

Then one computes vectors $d_k, z_{k+1}, y_{k+1}$, and scalars $c_k, (x_i^{k+1})_{i=1}^\infty$
as follows
for $k$ odd

\begin{equation}
    d_k = a_{\phi(\frac{k+1}{2})}
\end{equation}

\begin{equation}
    c_k = \max \left\{ (y_k, d_k), -x_{\phi(\frac{k+1}{2})} \right\}
\end{equation}

\begin{equation}
    \begin{cases}
        x_{i}^{k+1} = x_{i}^{k} & i \neq \phi(\frac{k+1}{2}) \\
        x_{i}^{k+1} = x_{i}^{k} + c_k & i = \phi(\frac{k+1}{2})
    \end{cases}
\end{equation}

\begin{equation}
    \begin{cases}
        z_{k+1} = z_{k} + c_k d_k \\
        y_{k+1} = b - z_{k+1}
    \end{cases}
\end{equation}

for $k$ even

\begin{equation}
    d_k = \begin{cases}
        z_k & z_k \neq 0 \\
        0 & z_k = 0
    \end{cases}
\end{equation}

\begin{equation}
    c_k = (y_k, d_k)
\end{equation}

\begin{equation}
    \begin{cases}
        x_{i}^{k+1} = x_{i}^{k} & \forall i \text{ if } z_k = 0 \\
        x_{i}^{k+1} = x_{i}^{k} \left( 1 + \frac{c_k}{||z_k||} \right) & \forall i \text{ if } z_k \neq 0
    \end{cases}
\end{equation}

\begin{equation}
    \begin{cases}
        z_{k+1} = z_{k} + c_k d_k \\
        y_{k+1} = b - z_{k+1}
    \end{cases}
\end{equation}
The first few steps of the CD Algorithm are:

\[ z_1 = 0 , \quad y_1 = b \Rightarrow x_1^1 = 0 \quad \forall i. \]

Assuming \((b, a_1) > 0\), we have for \(k = 1\):

\[
\begin{align*}
    d_1 &= a_1 \\
    x_1^2 &= c_1 = (b, a_1), \quad x_i^2 = 0 \quad \forall i \neq 1 \\
    z_2 &= c_1 a_1 = (b, a_1) a_1, \quad y_2 = b - (b, a_1) a_1,
\end{align*}
\]

and for \(k = 2\)

\[
\begin{align*}
    d_2 &= \frac{z_2}{||z_2||} = a_1 \\
    c_2 &= (y_2, d_2) = (b - (b, a_1) a_1, a_1) = (b, a_1) - (b, a_1) = 0 \\
    z_3 &= z_2, \quad y_3 = y_2.
\end{align*}
\]

2.1 Remarks

(a) The number of non-zero elements in the sequence \(\{x_i^{k+1}\}_{i=1}^\infty\) exceeds that of the sequence \(\{x_i^k\}_{i=1}^\infty\) by at most one.

(b) In Lemma 3.1 we prove that \(z_k = \sum_{i=1}^\infty x_i^k a_i\), where by remark (a) the sum on the right hand side is finite. Hence \(x_i^k\) can be interpreted as the "accumulated coefficient" of \(a_i\) in \(z_k\).
(c) If the spanning set \( \{ a_i \} \) is finite, with say \( n \) elements, the function \( \phi(k) \) should be redefined as:

\[
\phi(k) = k \quad 1 < k < n \\
\phi(n+k) = \phi(k) \quad k = 1, 2, \ldots
\]

With this modification the Algorithm will maintain the properties of the CD Algorithm, which are proved in the next sections.

3. Properties of the CD Algorithm

Some properties of the sequences generated by the CD Algorithm are given in the next four lemmas, and will be used eventually to prove its convergence.

Lemma 3.1

\[(3.1) \quad x_i^k > 0 \quad \forall i \]

\[(3.2) \quad z_k = \sum_{i=1}^{\infty} x_i^k a_i \quad , \quad k=1,2,\ldots \]

For \( k = 2, 3, \ldots \)

\[(3.3) \quad ||y_k||^2 \leq ||y_{k-1}||^2 - c_{k-1}^2 \]

\[(3.4) \quad ||y_k||^2 \leq ||b||^2 - \sum_{i=1}^{k-1} c_i^2 \]

Proof

Inequality (3.4) is a direct consequence of (3.3) and \( y_1=b \).

The other assertions are proved simultaneously by induction.
Step 1: $k = 1$ The relations (3.1) and (3.2) hold by (2.1). The proof of (3.3) for $k = 1$ is a special case of step 2.

Assuming the validity of (3.1) - (3.3) for $k$, we prove their validity for $k + 1$, dealing separately with odd and even $k$.

Step 2: **Odd $k$** To prove (3.1) note that for $i \neq \phi(k+1/2)$, $x_i^{k+1} = x_i^k \geq 0$ by induction, while for $i = \phi(k+1/2)$, $x_i^{k+1} = x_i^k + c_k \geq 0$ by (2.3). For (3.2) we have

$$z_{k+1} = z_k + c_k d_k$$

by (2.5)

$$= \sum_{i=1}^{\infty} x_i^k a_i + c_k d_k$$

by induction

$$= \sum_{i \neq \phi(k+1/2)} x_i^k a_i + x_{\phi(k+1/2)} + c_k a_{\phi(k+1/2)}$$

by (2.2)

$$= \sum_{i \neq \phi(k+1/2)} x_i^k a_i + (x_{\phi(k+1/2)} + c_k a_{\phi(k+1/2)})$$

by (2.4)

$$= \sum_{i = 1}^{\infty} x_i^{k+1} a_i$$

proving (3.2).

The inequality (3.3), for $k$ replaced by $k+1$ ($k$ odd) is obtained as follows:
\[ \|y_{k+1}\|_2^2 = \|y_k - c_k d_k\|_2^2 \quad \text{by (2.5)} \]

\[ = \|y_k\|_2^2 + c_k^2 - 2c_k (y_k, d_k) \text{, since } \|d_k\|_2 = \|a_{\phi(k+1)}\|_2 = 1. \]

By (2.3),

\[ \begin{cases} 
(y_k, d_k) = c_k \\
\text{or} \\
(y_k, d_k) \leq c_k = -x_{\phi(k+1)} \leq 0.
\end{cases} \]

In both cases,

\[ -2c_k (y_k, d_k) \leq -2c_k^2, \text{ hence} \]

\[ \|y_{k+1}\|_2^2 \leq \|y_k\|_2^2 + c_k^2 - 2c_k^2 = \|y_k\|_2^2 - c_k^2, \]

completing the proof in step 2.

**Step 2: even \(k\)** If \(z_k = 0\), \(x_i^{k+1} \geq 0\) \(\forall i\) by (2.8). Let \(z_k \neq 0\) and define \(f: \mathbb{R}^n \rightarrow \mathbb{R}\) by \(f(c) = \|y_k - c d_k\|_2^2\). This is a convex quadratic function which attains its minimum at \(c_k = (y_k, d_k)\).

Now (3.4) implies

\[ \|y_k\|_2^2 \leq \|b\|_2^2. \]

Since \(f(0) = \|y_k\|_2^2\), and

\[ f(-\|z_k\|) = \|y_k - (-\|z_k\|)\|_2^2 = \|y_k + z_k\|_2^2 = \|b\|_2^2, \]

\[ \frac{z_k}{\|z_k\|} \leq 0, \]

\[ \|y_k + z_k\|_2 \leq \|b\|_2, \]

\[ \|y_k\|_2 \leq \|b\|_2. \]
the inequality (3.6) is equivalent to \( f(0) \leq f(-||z_k||) \).

This implies

\[
f(-||z_k||) \leq f(c), \quad \forall c \leq -||z_k||,
\]

therefore \( c_k > -||z_k|| \) or \( 1 + \frac{c_k}{||z_k||} > 0 \)

and so \( x_i^{k+1} = x_i^k (1 + \frac{c_k}{||z_k||}) \geq 0 \).

By the above and (2.8)

\[
z_{k+1} = z_k + c_k d_k = z_k + c_k \frac{z_k}{||z_k||}
= (1 + \frac{c_k}{||z_k||}) \sum_{i=1}^{\infty} x_i^k a_i = \sum_{i=1}^{\infty} (1 + \frac{c_k}{||z_k||}) x_i^k a_i = \sum_{i=1}^{\infty} x_i^{k+1} a_i,
\]

which proves (3.2).

Finally, since (3.5) still holds for \( k \) even, the proof of (3.3) for \( k \) odd contains also the proof for \( k \) even. This completes the proof of the lemma. \( \square \)

**Lemma 3.2**

(3.7) \( \sum_{i=1}^{\infty} c_i^2 \leq ||b||^2 \) (Bessel inequality).

(3.8) \( \lim_{i \to \infty} c_i = 0 \),

(3.9) the sequence \( ||y_k|| \) is monotonically decreasing,
(3.10) \( z_k \in C \quad \forall k \in \mathbb{N} \).

**Proof**

By (3.4) \( \sum_{i=1}^{k} c_i^2 \leq \|b\|^2 \) for all \( k \). Hence the series \( \sum_{i=1}^{\infty} c_i^2 \) is convergent, Bessel inequality (3.7) holds, and the general term \( c_i \) of the series tends to zero, i.e. (3.8) holds. The validity of (3.9) is an immediate consequence of (3.3), while (3.10) follows from (3.1) and (3.2). Note again that by Remark 2.1 the series in (3.2) is finite. \( \square \)

The next result states roughly, that for \( k \) large enough, \( y_k \) is "almost" in the polar cone \( C^* \).

**Lemma 3.3**

For \( \varepsilon > 0 \) and \( z \in C \) fixed, there exists \( K \) such that

(3.11) \( (y_k, z) \leq \varepsilon \quad \forall k > K \).

**Proof**

We first prove (3.11) for the case where \( z = a_i \) for some \( i \). By (2.2) \( a_i \) appears periodically in \( \{d_k\} \). Denote by \( w \) the period of \( a_i \) in \( \{d_k\} \) (\( w \) may depend on \( i \)). By (3.8) we have

\[
|c_k| \leq \frac{\varepsilon}{w+1} \quad \forall k > K_i
\]

for some \( K_i \). We proceed to prove that (3.11) holds with \( K = K_i \). Indeed, fix \( k > K_i \), and let
\[ d_{k-l} = a_i, \quad 1 \leq l \leq k \]

(such \( l \) exists by periodicity of \( a_i \) in \( \{d_k\} \)). By (2.3) and (2.7) we have

\[ c_j \succ (y_j, d_j) \quad \forall j, \]

and by (2.5), (2.9)

\[
y_k = y_{k-1} - c_{k-1} d_{k-1} = y_{k-1} - \sum_{j=k-l}^{k-1} c_j d_j = y_{k-l} - \sum_{j \in J_1} c_j d_j
\]

where \( J_1 = \{j \in \mathbb{N}: k-l \leq j \leq k-1, d_j \neq 0\} \).

Hence

\[
(y_k, a_i) = (y_k, d_{k-l}) = (y_{k-l}, \sum_{j \in J_1} c_j d_j, d_{k-l}) =
\]

\[
= (y_{k-l}, d_{k-l}) - \sum_{j \in J_1} c_j (d_j, d_{k-l}) \leq
\]

\[
\leq c_{k-l} + \sum_{j \in J_1} |c_j| \cdot |(d_j, d_{k-l})| \leq c_{k-l} + \sum_{j \in J_1} |c_j| \cdot ||d_j|| \cdot ||d_{k-l}|| \text{ by Cauchy-Schwartz inequality}
\]

\[
= c_{k-l} + \sum_{j \in J_1} |c_j|, \quad \text{since } ||d_j|| = 1 \quad \forall j \in J_1.
\]
Now let $z$ be any element of $C$. Since $C = \text{span} \{ a_i \}$, the neighborhood of $z$

$$N(z; \frac{\varepsilon}{2||b||}) = \{ u : ||u-z|| \leq \frac{\varepsilon}{2||b||} \}$$

contains an element $v$ which can be expressed as a finite sum

$$v = \sum_{j \in J_2} x_j a_j, \quad x_j \geq 0 \quad \forall j \in J_2,$$

where $J_2$ is a finite index set of cardinality, say, $m$.

Define,

$$\theta = \frac{\varepsilon}{2m \max \{ x_j \}}.$$

By the first part of the lemma, there exists $K_j$ such that

$$\forall k \geq K_j,$$

Let $K = \max K_j$. By (3.12) - (3.13) we have $(y_k, v) \leq \frac{\varepsilon}{2}$, therefore

$$(y_k, z) = (y_k, v) + (y_k, z-v)$$

$$\leq \frac{\varepsilon}{2} + ||y_k|| \cdot ||z-v||$$
\[ \leq \frac{\epsilon}{2} + \frac{||b||}{2} \cdot \frac{\epsilon}{2||b||} = \epsilon, \text{ by (3.6) and } v \in N(z; \frac{\epsilon}{2||b||}). \]

This completes the proof. \( \square \)

The next lemma shows that the subsequences \( \{y_k\}, \{z_k\} \), \( k = 2, 4, 6, \ldots \) "tend to orthogonality".

**Lemma 3.4**

The subsequence \( \{(y_k, z_k); \ k \text{ even}\} \) satisfies

\[ (3.15) \quad \lim_{k \to \infty} (y_k, z_k) = 0. \]

**Proof**

By (2.9) and (3.6)

\[ ||z_k|| = ||b - y_k|| \leq ||b|| + ||y_k|| \leq 2||b||. \]

Hence for \( k \) even with \( z_k \neq 0 \), by (2.6)

\[ |(y_k, z_k)| = ||a_k|| |(y_k, d_k)| = ||z_k|| \cdot |c_k| \leq 2||b|| |c_k|. \]

The latter upper bound converges to zero, by (3.8), hence (3.15) follows. \( \square \)
4. Convergence of the CD Algorithm

We now combine the results of the previous section to prove our main result:

4.1 Convergence Theorem. The sequences \( \{Y_k\}, \{z_k\} \) generated by the CD Algorithm converge to the unique components \( y^*, z^* \) of the conic decomposition (1.6) respectively.

Proof

Using the properties (1.6) of the solution \( y^*, z^* \) one obtains

\[
|y_k - y^*|^2 = (y_k - y^*, y_k - y^*) = (y_k - y^*, (b - z_k) - (b - z^*))
\]

\[
= (y_k - y^*, z^* - z_k) = (y_k, z_k) - (y^*, z_k) - (y^*, z^*) + (y^*, z_k)
\]

\[
= (y_k, z^*) - (y_k, z_k), \text{ by orthogonality of } y^* \text{ and } z^*, \text{ and the facts } y^* \in \mathbb{C}, z_k \in \mathbb{C}. \text{ By Lemmas 3.3 and 3.4, this implies that for every } \epsilon > 0 \text{ there exists a large enough } K \text{ such that } |y_k - y^*|^2 < \epsilon
\]

for all \( k > K, k \) even. This proves convergence of the subsequence \( \{y_k\}, k \) even.

By (3.9) the sequence \( \|y_k\|_{k=1}^\infty \) is monotone. Since it has a convergent subsequence, the entire sequence \( \|y_k\| \) must converge to \( \|y^*\| \), i.e.,

\[
\lim_{k \to \infty} |y_k| = |y^*|.
\]

The final step of the proof is to show that the convergence in norm (4.1) implies the convergence \( y_k \to y^* \). Now,
\[ \|y_k\|^2 = \|b-z_k\|^2 = \|y^* + z - z_k\|^2 \]
\[ = \|y^*\|^2 + \|z - z_k\|^2 + 2(y^*, z - z_k) \]
\[ = \|y^*\|^2 + \|y_k - y^*\|^2 - 2(y^*, z_k). \]

Therefore
\[ \|y_k - y^*\|^2 = \|y_k\|^2 - \|y^*\|^2 + 2(y^*, z_k) \]
\[ \leq \|y_k\|^2 - \|y^*\|^2 \quad \text{since} \quad y^* \in C^*, z_k \in C. \]

The latter inequality together with (4.1) imply
\[ \|y_k - y^*\|^2 \geq 0, \text{ or } y_k = y^*. \]

Since \( z_k = b - y_k, z_k + b - y^* = z^* \), and the proof is completed. \( \Box \)

4.2 Remarks

(a) The choice of the initial projection \( z_1 = 0 \) in the CD Algorithm is merely for convenience. In fact \( z_1 \) can be chosen to be any element of \( C \) without affecting the validity of the preceding results. In this sense Theorem 4.1 is a global convergence result.

(b) In the CD Algorithm, \( a_i \) appears periodically in the sequence \( \{d_k\}_{k=1}^\infty \), with period \( 2^{i+1} \). This choice is by no means unique in order to guarantee convergence. Any choice for which
the distance between consecutive occurrences of $a_i$ in $(d_k)$ is bounded will do.

5. The Subspace Case

In this section we discuss the case where $C$ is a subspace spanned by \{a_1, a_2, \ldots\}. The CD Algorithm can be simplified in this case and the resulting expansion has greater resemblance to the classical Fourier expansion.

The non-orthogonal case. Let $C = \text{span} \{a_1, a_2, \ldots\}$ where the $a_i$'s are arbitrary elements in $l_2$ (in particular they may be non-orthogonal, or even linearly dependent.) Here the series \{x_i\} in the CD Algorithm can be dispensed with, and (2.3) is replaced by

\begin{equation}
(2.3a) \quad c_k = (y_k, d_k).
\end{equation}

A careful examination of the results of sections 2-4 reveals that they remain valid, with the following strengthening of the results (3.4), (3.11) respectively:

\begin{equation}
(5.1) \quad ||y_{k+1}||^2 = ||b||^2 - \sum_{i=1}^{k} c_i^2 \forall k,
\end{equation}

\begin{equation}
(5.2) \quad \lim_{k \to \infty} (y_k, z) = 0.
\end{equation}
Moreover, a necessary and sufficient condition for equality to hold in the Bessel inequality (3.7) can be added:

\[
\sum_{i=1}^{\infty} c_i^2 = ||b||^2 \quad \text{(Parseval's formula)}
\]

(5.3)

if and only if \( bc \in C \).

Indeed by (5.1), \( \sum_{i=1}^{\infty} c_i^2 = ||b||^2 - ||y^*||^2 \). Hence (5.3) holds if and only if \( y^* = 0 \) or equivalently \( bc \in C \).

**The Orthogonal Case.** Let \( C \) be the subspace spanned by the orthonormal basis \( \{a_i\} \). We show that in this case the expansion generated by the CD Algorithm (with the modification (2.3a) is a generalization of the classical Fourier expansion, in the sense that the non-zero elements of the former coincide with the elements of the latter. More precisely,

**Proposition 5.1.** Let \( \{c_i\} \) and \( \{d_i\} \) be the sequences generated by the CD Algorithm for the projection \( z^* = \sum_{i=1}^{\infty} c_i d_i \), and let \( a_i = (b, a_i) \) be the Fourier coefficient in the representation \( z^* = \sum a_i a_i \). Then

\[
(5.4) \quad c_i = \begin{cases} a_k, & i = 2^k - 1 \\ 0, & \text{otherwise} \end{cases} \quad \text{and} \quad d_i = \begin{cases} a_k a_k, & i = 2^k - 1 \\ 0, & \text{otherwise} \end{cases}
\]

**Proof.** Let

\[
- z_1 = 0, \quad z_{k+1} = \sum_{i=1}^{k} a_i a_i, \quad y_k = b - z_k, \quad k = 1, 2, \ldots
\]
and \( C_k = \text{span} \{ a_i \}_{i=1}^k \). We prove (5.4) by induction on \( i \). For \( i = 1 \) we have \( c_1 = a_1 = (b_1, a_1) \) and \( d_1 = a_1 \) by (2.2). Assume that (5.4) holds for \( i = 1, \ldots, n-1 \). From this and \( z_1 = z_1 = 0 \) it follows that

\[
z_k = \sum_{\ell=1}^{2^k} c_\ell d_\ell = \sum_{j=1}^k a_j a_j = z_{k+1},
\]

since \( c_\ell \neq 0 \) only if \( \ell \) is of the form \( \ell = 2^{j-1} \), and for such \( j \), \( d_\ell = a_j \) and \( c_\ell = a_j \) by (5.4). Hence if \( i = 2^k \), \( z_i = z_1 + \log_i \), and by (5.4) for all \( i \)

\[
(5.5) \quad z_i = z_1 + \lfloor \log_i \rfloor
\]

Where \( \lfloor r \rfloor \) denotes the integer part of \( r \). The induction hypothesis now shows that (5.5) holds for \( i = 1, \ldots, n \), since \( z_n \) is the \( (n-1) \)-th partial sum of the series \( \sum_{i=1}^\infty c_i d_i \). Further, since the Fourier expansion satisfies \( y_{k+1} \epsilon C_k \), one obtains

\[
(5.6) \quad y_i = b - z_i = b - z_1 + \lfloor \log_i \rfloor = y_1 + \lfloor \log_i \rfloor \in C_{\lfloor \log_i \rfloor},
\]

for \( i = 1, \ldots, n \). If \( 2^{k-1} \leq n \leq 2^k-1 \), then \( \lfloor \log_i \rfloor = k-1 \) and by (5.6) \( y_n \in C_{k-1} \). By (2.2), (2.6), the first appearance of \( a_k \) in the sequence \( \{ d_i \} \) is for \( i = 2^k-1 \), therefore \( d_n \in C_{k-1} \), and \( c_n = (y_n, d_n) = 0 \). If \( n = 2^k-1 \), then \( \lfloor \log_2(n-1) \rfloor = k-1, y_{n-1} = \bar{y}_k \) by (5.6), and \( d_n = a_k \) by (2.2), implying \( c_n = (y_n, d_n) = \)
(\text{6.1}) \quad x_i = b_i + \lambda_{i-1} - \lambda_i \quad i = 1, \ldots, n,

(\text{6.2}) \quad x_{i+1} - x_i \geq 0

(\text{6.3}) \quad \lambda_i (x_{i+1} - x_i) = 0 \quad i = 1, \ldots, n-1

(\text{6.4}) \quad \lambda_0 = \lambda_n = 0, \quad \lambda_i > 0

where \( \lambda_i \) is the instantaneous reaction between the \( i \)-th and \( (i+1) \)-st ball, and \( x_i \) is the initial acceleration of the \( i \)-th ball multiplied by its mass at \( t=0 \). The quantities \( b_i \) are given in terms of the geometry of the tube.

Defining \( u_i = \lambda_{i-1} - \lambda_i \), it is shown by Mackie that the problem is equivalent to finding vectors \( x, u \) such that

(\text{6.5}) \quad b = x + u, \quad (x, u) = 0, \quad x \in K, \quad u \in K^*

where \( K \) is the set of vectors satisfying (\text{6.2}), i.e.

(\text{6.6}) \quad K = \{x : x^T \Lambda \geq 0\}

and the matrix \( \Lambda \) is given componentwise by
It is well known that the polar of a cone given in the form (6.6) is \( K^* = \text{cone} \{ a_i \}_{i=1}^n \), \( a^i = i\)-th column of A. Since \( K^{**} = K \), problem (6.5) can be now reformulated in the format needed for our purposes, namely: find \( z, y \in \mathbb{R}^{n+1} \) such that

\[
b = z + y, \quad (z, y) = 0, \quad z \in C_n, \quad y \in C^*_n
\]

where \( C_n = \text{cone} \{ a_i \}_{i=1}^n \) and \( C^*_n = \{ y \in \mathbb{R}^{n+1}: \ y_{i+1} - y_i \geq 0 \ \text{for} \ i = 1, \ldots, n \} \).

As a specific example consider the decomposition of \( b = (-1, 1, 0, \ldots, 0) \in \mathbb{R}^{n+1} \). Using the CD Algorithm for \( n = 4 \), we obtained a sequence converging to \( z^* = (0, \frac{3}{4}, -\frac{1}{4}, -\frac{1}{4}, -\frac{1}{4}) \), \( y^* = (-1, -\frac{1}{4}, -\frac{1}{4}, -\frac{1}{4}, -\frac{1}{4}) \), which suggested that the solution for general \( n \) is given by

\[
(6.8) \quad z^*_n = (0, \frac{n-1}{n}, -\frac{1}{n}, \ldots, -\frac{1}{n}), \quad y^*_n = (-1, -\frac{1}{n}, -\frac{1}{n}, \ldots, -\frac{1}{n}).
\]

This is indeed the solution: the relations \( z^*_n \in C_n \) and \( (y^*_n, z^*_n) = 0 \) are easily verified, while the condition \( z_n \in C_n \) follows by noting the explicit representation \( z^*_n = \sum_{k=2}^{n} (1 - \frac{k-1}{n}) a_k \).

Turning to the case where the number of balls is infinite, we now deal with a problem in the Hilbert space \( l_2 \). Using the natural imbedding of \( \mathbb{R}^{n+1} \) in \( l_2 \), i.e., \( x \in \mathbb{R}^{n+1} \) corresponds to
(x_1, \ldots, x_{n+1}, 0, 0, \ldots) \in \ell_2$, the cone $C$ is now given as the conic hull of $a_i \in \ell_2$ given by (6.7). A look at (6.8) suggests that

$$(6.9) \quad z^* = (0, 1, 0, 0, \ldots), \quad y^* = (-1, 0, 0, \ldots)$$

is the solution in this case. Indeed, the relations $y^* \in C^*$, $(z^*, y^*) = 0$ can be verified by a direct computation. Finally,

$z^* = \lim_{n \to \infty} z_n \in C$ since $z_n \in C$ and $C$ is closed.

Observe that though $z^* \in C$, it cannot be expanded directly as a non-negative linear combination (finite or infinite) of the $a_i$'s.
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References


The problem considered is that of constructing the decomposition of a vector in a Hilbert space into two orthogonal components; one (the "projection") in a given cone, and the other in the polar cone. The projection $Z^*$ can be expressed as a Fourier type expansion. An algorithm for constructing this expansion is given, and shown to converge to $Z^*$.
Conic decomposition
Optimization in Hilbert space
Projection on convex cone
Convex cone
Fourier series