SYMMETRIC INTEGRO-DIFFERENTIAL-BOUNDARY PROBLEMS

BY

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ABSTRACT. Necessary and sufficient conditions for a linear vector integro-differential-boundary problem to be symmetric (selfadjoint) are developed, and then applied to obtain canonical forms of such symmetric problems. Moreover, the formulation of the integro-boundary conditions herein yields a simplification of one of the conditions for selfadjointness of a differential-boundary operator previously announced.

1. Introduction. Necessary and sufficient conditions for a class of differential-boundary operators to be selfadjoint, recently given by Krall [3], will be extended to integro-differential-boundary problems, in vector form,

\begin{align}
A_1(x)y' + A_0(x)y + H(x)[M_2y(a) + N_2y(b)] + K(x) \int_a^b F(t)y\,dt &= \lambda B(x)y, \\
My(a) + Ny(b) + \int_a^b F(t)y\,dt &= 0.
\end{align}

In addition, for the special case \( K(x) = 0 \) the formulation of the conditions (1.1b) herein allows a simplification of one of the conditions in [3].

A suitable formulation of a problem adjoint to a differential system with integral-boundary conditions has been the subject of a number of papers, among them [1], [2], [3] and [5]. However, the definition of symmetry (selfadjointness) adopted in this paper is more in accordance with that employed for boundary problems (see, for example, [4, p. 197]) than the requirement used in [3]. Moreover, while the integral term in (1.1a) may be replaced by a boundary term in view of condition (1.1b), nevertheless, there is an extra measure of generality in this setting that is unavailable in [3].

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The adjoint problem will be developed and necessary and sufficient conditions for symmetry will be derived in §2 for problems wherein the form of the integral-boundary condition (1.1b) is an extension of that used in [5]. Canonical forms for classes of equivalent symmetric integro-differential-boundary problems (1.1a), (1.1b) will then be constructed in §3.

Matrix and vector notation will be employed throughout. Matrices of various dimensional orders will be denoted by both italic and Greek capital letters, while vectors will be represented by lower-case italic letters. The operations of differentiation and conjugate-transpose for both matrices and vectors will be indicated by ' and *, respectively. Moreover, as is customary, 0 will be used indiscriminately to denote either the number zero, a zero matrix or a zero vector; the $\sigma \times \sigma$ identity matrix will be indicated by $I_{\sigma}$, and $i$ will denote a complex square root of $-1$. Finally, when row and column dimensions agree, $[M, N; P, Q]$ will represent the matrix $[M \quad P \quad N \quad Q]$.

2. Necessary and sufficient conditions. For the problem (1.1a), (1.1b) it will be assumed that the elements of the $n \times n$ matrix $A(x)$ are of class $C'$ on the finite interval $a < x < b$, the elements of the $n \times n$ matrices $A_0(x)$ and $B(x)$, the $m \times n$ matrix $F(x)$, the $n \times m$ matrix $K(x)$, and the $n \times p$ matrix $H(x)$ are continuous on $[a, b]$, $\lambda$ is a scalar parameter, $M_2$ and $N_2$ are each $p \times n$ constant matrices, and $M$ and $N$ are each $m \times n$ constant matrices, $0 \leq m \leq 2n$, such that the $m$ boundary forms (1.1b) are linearly independent. A necessary and sufficient condition for the latter assumption is that the rows of the $m \times 3n$ matrix $[M \quad N \quad F(x)]$ are linearly independent on $a \leq x \leq b$ (Jones, [2, Theorem 2.1]).

Now, by a linear rearrangement of its rows, we may place the boundary conditions (1.1b) in the form

$$
M_0 y(a) + N_0 y(b) = 0,
$$

$$(2.1b) \quad M_1 y(a) + N_1 y(b) + \int_a^b F_1(t) y dt = 0,$$

$$
\int_a^b F_2(t) y dt = 0,
$$

where $M_0$ and $N_0$ are each $\rho \times n$ constant matrices with $[M_0 \quad N_0]$ having rank $\rho$, $M_1$ and $N_1$ each $\sigma \times n$ matrices with $[M_1 \quad N_1]$ having rank $\sigma$, $F_1(x)$ and $F_2(x)$, respectively, $\sigma \times n$ and $\tau \times n$ matrices such that the $\sigma + \tau$ rows of $F_1(x)$ and $F_2(x)$ are a set of $\sigma + \tau$ linearly independent vectors on $[a, b]$, the $\rho + \sigma$ rows of $[M_0 \quad N_0]$ and $[M_1 \quad N_1]$ are linearly independent, and $\rho + \sigma + \tau = m$. Moreover, as this transformation may be effected by multiplying (1.1b) on the left by a suitable $m \times m$ nonsingular constant matrix $D$, the partitioning of $K(x)D^{-1} = [K_0(x) \quad K_1(x) \quad K_2(x)]$ into $\rho$, $\sigma$ and $\tau$ columns, respectively, in view of the last
boundary condition of \((2.1b)\), reduces \((1.1a)\) to the form

\[
A_1(x)y' + A_0(x)y + H(x)[M_2y(a) + N_2y(b)] + K_1(x) \int_a^b F_1(t)y \, dt = \lambda B(x)y.
\]

Furthermore, without loss of generality, we may assume that \(\rho = 2n - (\rho + \sigma)\) and that the \(2n \times 2n\) matrix

\[
\begin{bmatrix}
M_0 & N_0 \\
M_1 & N_1 \\
M_2 & N_2
\end{bmatrix}
\]

is nonsingular (see, for example, Remark 6.2 of [5]).

Transforming the integro-differential-boundary problem \((2.1a), (2.1b)\) into an equivalent two-point boundary problem in a manner analogous to that employed in [2], [3] and [5] yields the adjoint problem. Introducing new vectors

\[
\begin{align*}
u_1 &= M_1y(a) + \int_a^x F_1(t)y \, dt, \\
u_2 &= \int_a^x F_2(t)y \, dt, \\
s_1 &= u_1(b) - u_1(a) = \int_a^b F_1(t)y \, dt, \\
s_2 &= M_2y(a) + N_2y(b),
\end{align*}
\]

problem \((2.1a), (2.1b)\) is equivalent to the system consisting of \((3n + \sigma + r - \rho)\) linear differential equations and \(2n + 2(\sigma + r)\) end-point conditions:

\[
A_1(x)y' + A_0(x)y + K_1(x)s_1 + H(x)s_2 = \lambda B(x)y,
\]

\[
\begin{align*}
u_1' - F_1(x)y &= 0, \\
u_2' - F_2(x)y &= 0,
\end{align*}
\]

\[
\begin{align*}
s_1' &= 0, \\
s_2' &= 0,
\end{align*}
\]

\[
\begin{align*}
M_0y(a) + N_0y(b) &= 0, \\
M_1y(a) - u_1(a) &= 0, \\
N_1y(b) + u_1(b) &= 0,
\end{align*}
\]

\[
\begin{align*}
u_1(a) &= 0, \\
u_1(b) &= 0,
\end{align*}
\]

\[
\begin{align*}
u_2(a) + s_1(a) - u_1(b) &= 0, \\
M_2y(a) - s_2(a) + N_2y(b) &= 0.
\end{align*}
\]

Now, if the inverse of \((2.2)\) is introduced and partitioned,

\[
\begin{bmatrix}
M_0 & N_0 \\
M_1 & N_1 \\
M_2 & N_2
\end{bmatrix}
\begin{bmatrix}
P_0 & -P_1 & -P_2 \\
Q_0 & Q_1 & Q_2
\end{bmatrix} = I_{2n},
\]

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where \( P_0 \) and \( Q_0 \) are each of dimension \( n \times \rho \), \( P_1 \) and \( Q_1 \) each of \( n \times \sigma \), and \( P_2 \) and \( Q_2 \) each of \( n \times \rho \), then the system adjoint to (2.3) is readily obtained (see, for example, [4, §3.6]), being comprised of \( 3n + \sigma + r - \rho \) differential equations and \( 4n - 2\rho \) end-point conditions:

\[
\begin{align*}
-[A^*_1(x)z]' + A^*_0(x)z - F^*_1(x)v_1 - F^*_2(x)v_2 &= \lambda B^*_z(x), \\
v_1 &= 0, \\
-v_2 &= 0,
\end{align*}
\]

\[\begin{align*}
-t_1' + K^*_1(x)z &= 0, \\
-t_2' + H^*_z(x)z &= 0,
\end{align*}\]

(2.5)

\[
\begin{align*}
P^*_2A^*_1(a)z(a) + Q^*_2A^*_1(b)z(b) + P^*_2M^*_1v_1(a) - Q^*_2N^*_1v_1(b) - t_2(a) &= 0, \\
P^*_1A^*_1(a)z(a) + Q^*_1A^*_1(b)z(b) + P^*_1M^*_1v_1(a) - Q^*_1N^*_1v_1(b) + t_1(a) &= 0, \\
t_1(b) &= 0, \\
t_2(b) &= 0.
\end{align*}
\]

Then, eliminating \( v_1, t_1 \) and \( t_2 \) with the aid of relation (2.4), the problem

\[
\begin{align*}
-[A^*_1(x)z]' + A^*_0(x)z - F^*_1(x)v_1 - F^*_2(x)v_2 &= \lambda B^*_z(x), \\
v_1 &= 0, \\
-t_2' + H^*_z(x)z &= 0,
\end{align*}
\]

(2.6a)

\[
\begin{align*}
P^*_2A^*_1(a)z(a) + Q^*_2A^*_1(b)z(b) + \int_a^b K^*_1(\xi)z d\xi - F^*_2(x)v_2 &= \lambda B^*_z(x), \\
v_2 &= \text{constant},
\end{align*}
\]

(2.6b)

\[
\begin{align*}
P^*_2A^*_1(a)z(a) + Q^*_2A^*_1(b)z(b) + \int_a^b H^*_z(\xi)z d\xi &= 0
\end{align*}
\]

will be defined as the integro-differential-boundary problem adjoint to problem (2.1a), (2.1b).

It is to be noted that, in general, the parameter \( v_2 \) cannot be eliminated from (2.6a). However, for the problems discussed by Krall [3] it was assumed that \( r = 0 \), and, hence, an adjoint problem not involving a parameter may be introduced. In addition, it is readily verifiable that the adjoint problem (2.6) is independent of a reformulation of system (2.1a), (2.1b) into an equivalent problem by the addition to (2.1a) of terms of the form

\[
\begin{align*}
J_0(x)[M_0y(a) + N_0y(b)] \\
+ J_1(x)\left[M_1y(a) + N_1y(b) + \int_a^b F_1(\xi)y d\xi\right] + J_2(x)\int_a^b F_2(\xi)y d\xi,
\end{align*}
\]

\[J_i(x) (i = 1, 2, 3) \text{ continuous on } [a, b].\] This invariance property of the adjoint will be applied in developing canonical forms in the next section.

A problem (2.1a), (2.1b) will be termed symmetric if the integral-boundary
forms (2.1b) and (2.6b) are equivalent and the integro-differential-boundary operators in (2.1a) and (2.6a) coincide when applied to vectors of class $C'$ satisfying the integro-boundary conditions (2.1b). This terminology is an extension of that applied to differential expressions in [4, p. 122] and corresponds to the definition of selfadjointness in [4, p. 197]. Focusing our attention first on the integral-boundary conditions, we have the following generalization of results contained in Theorem 5.1 of [3].

**Lemma 2.1.** For a problem (2.1a), (2.1b) the integro-boundary forms (2.1b) and (2.6b) of the adjoint problem are equivalent if and only if

(a) $p + \sigma = n$ and $\tau = 0$, or equivalently, $m = p = n$,

(b) $[M_0, N_0; M_1, N_1] \cdot \text{diag} \{ - A_1^{-1}(a), A_1^{-1}(b) \} \cdot [M_0, N_0; M_1, N_1]^* = 0$, and

(c) $H(x) = F_1^*(x)E_1$ on $[a, b]$, where $E_1 = [0 I_p]E$, $E = C^{-1}$, and

\[ C = [M_2 N_2] \cdot \text{diag} \{ - A_1^{-1}(a), A_1^{-1}(b) \} \cdot [M_0, N_0; M_1, N_1]^*. \]

As the rank of the $p \times 2n$ matrix $[P_2^* A_1^*(a) Q_2^* A_1^*(b)]$ is $p$, equivalence of the integro-boundary forms (2.1b) and (2.6b) requires that $m = p = \rho + \sigma$, whence (2.7a) follows. Then, under (2.7a) a necessary and sufficient condition for equivalence of the integro-boundary forms is the existence of an $n \times n$ constant nonsingular matrix $E$ such that

\[ P_2^* A_1^*(a) Q_2^* A_1^*(b) = E^*[M_0, N_0; M_1, N_1], \]

(2.8)

\[ H^*(x) = E^*[0 F_1^*(x)]^* \quad \text{on} \quad [a, b]. \]

(2.9)

Now, it follows from relation (2.4) that (2.7b) and (2.8) are equivalent with $E$ as given in (2.7c). For this latter equivalence we first note that, as (2.7b) is an immediate consequence of (2.8), the nonsingularity of the matrix $C$, defined in (2.7c), follows either by a method analogous to that used in [3, p. 445] or, as (2.7b) is an immediate consequence of (2.8) for some nonsingular $E$, from the fact that the rows of $[M_2 N_2]$ are linearly independent of the rows of $[M_0, N_0; M_1, N_1]$, while the latter rows constitute a maximal linearly independent vector set orthogonal to the $2n$ columns of $\text{diag} \{ - A_1^{-1}(a), A_1^{-1}(b) \} \cdot [M_0, N_0; M_1, N_1]^*$. Then, with $E$ defined as in (2.7c), (2.8) follows from (2.7b) and the fact that the matrices $P_2$ and $Q_2$ are uniquely determined by the relations (2.4). Finally, (2.7c) and (2.9) are clearly equivalent under the definition of $E_1$ in (2.7c).
Lemma 2.2. Under equivalence of the integro-boundary forms (2.1b) and (2.6b), problem (2.1a), (2.1b) is symmetric if and only if there exists a $\sigma \times \sigma$ constant Hermitian matrix $\Gamma$ such that on $a \leq x \leq b$

\[
\begin{align*}
(a) & \quad A^*_1(x) = -A_1(x), \quad A^*_0(x) = A_0(x) - A^*_1(x), \quad B^*(x) = B(x), \\
(b) & \quad K(x) = F_1^*[x][\Gamma + \frac{1}{\tau} \Theta], \quad \Theta = P_1^*A_1^*(a)P_1 - Q_1^*A_1^*(b)Q_1.
\end{align*}
\]

For a symmetric problem the relations in the first condition follow from term-by-term identification of corresponding operators when applied to vectors $y$ of class $C'$ satisfying $y(a) = y(b) = \int_a^b F_1(t)y dt = \int_a^b K_1(t)y dt = 0$. Then, under (2.7) and (2.10a), a necessary and sufficient condition for problem (2.1a), (2.1b) to be symmetric is that

\[
\begin{align*}
F_1^*[x][\{(E_1M_2 + P_1^*A_1^*(a))y(a) + (E_1N_2 + Q_1^*A_1^*(b))y(b)\} \\
- F_1^*[x] \int_a^b K_1^*(t)y dt + K_1(x) \int_a^b F_1(t)y dt = 0
\end{align*}
\]

on $[a, b]$ for arbitrary vectors $y$ of class $C'$ satisfying (2.1b), wherein $\tau = 0$. Now, for vectors $y \in C'$ such that $y(a) = y(b) = \int_a^b F_1(t)y dt = \int_a^b K_1^*(t)y dt = 0$, we have that $F_1^*[x] \int_a^b K_1^*(t)y dt = 0$; and, as the $\sigma$ columns of $F_1^*[x]$ are linearly independent on $[a, b]$, $\int_a^b K_1^*(t)y dt = 0$. Consequently, it follows that $\int_a^b F_1^*(t)v dt = 0$ for arbitrary continuous vectors $v(t)$ satisfying $\int_a^b F_1^*(t)v dt = 0$. In addition, as $\int_a^b F_1(t)F_1^*(t) dt$ is nonsingular, let the $\sigma \times \sigma$ constant matrix $\Phi$ be determined by $\int_a^b F_1^*(t)[K_1(t) - F_1^*(t)\Phi] dt = 0$. Then, for $v(t) = [K_1(t) - F_1^*(t)\Phi] c$, $c$ an arbitrary $\sigma$-dimensional constant vector, we have that $\int_a^b [K_1(t) - \Phi^*F_1(t)]v dt = 0$, and, consequently,

\[
K_1(x) = F_1^*[x]\Phi \quad \text{on} \ [a, b].
\]

Moreover, under (2.12), in view of the linear independence of the columns of $F_1^*[x]$ on $[a, b]$, condition (2.11) for vectors $y \in C'$ satisfying (2.1b) with $\tau = 0$ reduces to the requirement that

\[
(E_1M_2 + P_1^*A_1^*(a) - \Theta M_1)y(a) + (E_1N_2 + Q_1^*A_1^*(b)) - \Theta N_1)y(b) = 0,
\]

where $\Theta = \Phi - \Phi^*$, for arbitrary vectors $y(a), y(b)$ such that $M_0y(a) + N_0y(b) = 0$. Now, as the $n + \sigma$ columns of $[-P_1, -P_2; Q_1, Q_2]$ form a maximal set of linearly independent vectors orthogonal to the $\rho$ rows of $[M_0, N_0]$, relation (2.13) for $y(a), y(b)$ satisfying $M_0y(a) + N_0y(b) = 0$ holds if and only if
(2.14) \[-(E_1 M_2 + P_1^* A_1^*(a) - \Theta M_1) P_1 + (E_1 N_2 + Q_1^* A_1^*(b) - \Theta N_1) Q_1 = 0,\]

\[-(E_1 M_2 + P_1^* A_1^*(a) - \Theta M_1) P_2 + (E_1 N_2 + Q_1^* A_1^*(b) - \Theta N_1) Q_2 = 0;\]

or, equivalently, if and only if

(2.15) \[\Theta = -P_1^* A_1^*(a) P_1 + Q_1^* A_1^*(b) Q_1,\]

(2.16) \[E_1 = P_1^* A_1^*(a) P_2 - Q_1^* A_1^*(b) Q_2.\]

However, (2.16) reduces to an identity under (2.8) and (2.10a). Consequently, on setting \(\Gamma = \frac{1}{2}(\Phi + \Phi^*)\) we have \(\Phi = \Gamma + \frac{1}{2}\Theta\), and the lemma is established.

Moreover, as conditions (2.14) are equivalent to the existence of an \(\sigma \times \rho\) constant matrix \(J\) such that

(2.17) \[E_1 M_2 + P_1^* A_1^*(a) - \Theta M_1 = J M_0, \quad E_1 N_2 + Q_1^* A_1^*(b) - \Theta N_1 = J N_0,\]

on substituting the values of \(P_1\) and \(Q_1\) from (2.17) into (2.15) it follows, from the definition of \(E_1\) in (2.7c), that

(2.18) \[\Theta = E_1 (\frac{1}{2} M_2 A_1^{-1}(a) M_2^* + N_2 A_1^{-1}(b) N_2^*) E_1.\]

On the other hand, for \(K_1(x)\) of the form (2.12) with \(\Phi = \Gamma + \frac{1}{2}\Theta\), \(\Gamma\) a \(\sigma \times \sigma\) constant Hermitian matrix and \(\Theta\) given by (2.18), we have from (2.4) and (2.7b) that \(P_1\) and \(Q_1\) satisfy relations (2.17) with \(J = E_1 (\frac{1}{2} M_2 A_1^{-1}(a) M_2^* + N_2 A_1^{-1}(b) N_2^*) E_0, E_0 = [I, 0] E,\) and that \(\Theta\) satisfies (2.15). Combining these facts with the two lemmas yields the following result.

**Theorem 2.1.** The integro-differential-boundary problem (2.1a), (2.1b) is symmetric (selfadjoint) if and only if there exists a \(\sigma \times \sigma\) constant Hermitian matrix \(\Gamma\) such that on \(a \leq x \leq b\)

(a) \(\rho + \sigma = n\) and \(r = 0,\)

(b) \([M_0, N_0; M_1, N_1] \cdot \text{diag} \{-A_1^{-1}(a), A_1^{-1}(b)\} \cdot [M_0, N_0; M_1, N_1]^* = 0,\)

(2.19)

(c) \(A_1^*(x) = -A_1(x), A_0^*(x) = A_0(x) - A_1(x), B^*(x) = B(x),\)

(d) \(H(x) = F_1^*(x) E_1,\)

(e) \(K_1(x) = F_1^*(x) [\Gamma + \frac{1}{2}\Theta].\)
where $E_1$ is given in (2.7c) and $\Theta$ in (2.18).

For the special case $K_1(x) = 0$ considered by Krall [3], condition (2.19e) reduces to $\Theta = 0$ in view of the linear independence of the columns of $F_1^*(x)$ on $[a, b]$. This simplification of the condition corresponding to condition (5.7) of Theorem 5.1 of [3] accrues from the above formulation of the integro-boundary conditions notwithstanding the more restrictive equivalence of terms under self-adjointness in [3].

Corollary. An integro-differential-boundary problem (2.1a), (2.1b) with $K_1(x) = 0$ on $[a, b]$ is symmetric if and only if relations (2.19a, b, c, d) hold on $[a, b]$ and $E_j(M_2 A_j^{-1}(a) M_2^* - N_2 A_j^{-1}(b) N_2^*) E_j^* = 0$, $E_1$ defined in (2.7c).

3. Canonical forms. For a symmetric integro-differential-boundary problem

\[ A_1(x) y' + A_0(x) y + H(x)[M_2 y(a) + N_2 y(b)] + K_1(x) \int_a^b F_1(\theta) y d\theta = \lambda B(x) y, \]

(3.1)

\[ M_0 y(a) + N_0 y(b) = 0, \]

\[ M_1 y(a) + N_1 y(b) + \int_a^b F_1(\theta) y d\theta = 0, \]

with the $\rho \times 2n$ matrix $[M_0 N_0]$, the $\sigma \times 2n$ matrix $[M_1 N_1]$, the $n \times 2n$ matrix $[M_2 N_2]$ and the $2n \times 2n$ matrix (2.2) each having maximal rank, and the $\sigma$ rows of $F_1(x)$ linearly independent on $[a, b]$, it may be assumed, without loss of generality, that the orthogonality condition

\[ M_0 M_0^* + N_0 N_0^* = 0 \]

(3.2)

holds. For, as the $\rho \times \rho$ matrix $W_0 = M_0^* M_0 + N_0^* N_0$ is nonsingular, the orthogonality relation (3.2) prevails upon adding to the last $\sigma$ integro-boundary conditions of (3.1) the first $\rho$ conditions premultiplied by $- (M_1 M_1^* + N_1 N_1^*) W_0^{-1}$; or equivalently, by premultiplying the integro-boundary conditions of (3.1) by the $n \times n$ nonsingular matrix

\[ [I_{\rho}, 0; -(M_1 M_1^* + N_1 N_1^*) W_0^{-1}, I_{\rho}]. \]

(3.3)

Moreover, inasmuch as the new integro-boundary conditions are equivalent to the original and the matrices $H(x)$, $K_1(x)$, $F_1(x)$, $M_0$, $N_0$, $M_2$, $N_2$, $P_1$, $Q_1$, $P_2$, $Q_2$, $E_1$ and $\Theta$ are unaffected by this change of $M_1$ and $N_1$, conditions (2.19) remain valid and the symmetry of the problem is preserved. It is to be noted that while the matrix $C$ undergoes a postmultiplication by the conjugate-transpose of (3.3)
the matrix $E_1$ remains unaltered. In this section we shall assume that the orthogonality condition (3.2) holds.

Now, as
\[-E_1M_2A_1^{-1}(a)M_0^* + E_1N_2A_1^{-1}(b)N_0^* = 0\]

from the definition of $E_1$ in (2.7c), and a maximal set of $2n - \rho$ linearly independent vectors of the null space of $[-M_0A_1^{*\rho}(a)N_0A_1^{*\rho}(b)]$ is given by the columns of the $2n \times (n + \rho)$ matrix

\[
\begin{bmatrix}
M_0^* & M_1^* - A_1^*(a)M_1^* \\
N_0^* & N_1^* - A_1^*(b)N_1^*
\end{bmatrix}
\]

in view of (2.19b) and (3.2), it follows that there exist $\sigma \times \rho$, $\sigma \times \sigma$ and $\sigma \times \sigma$ constant matrices $R$, $S$ and $T$, respectively, such that

(3.4) \quad E_1M_2 = RM_0 + SM_1 - TM_1A_1(a), \quad E_1N_2 = RN_0 + SN_1 + TN_1A_1(b).

On postmultiplying these two relations by $-A_1^{-1}(a)M_1^*$ and $A_1^{-1}(b)N_1^*$, respectively, and adding, we have that $I_\sigma = TW_1$, where

(3.5) \quad W_1 = M_1M_1^* + N_1N_1^*

is a $\sigma \times \sigma$ nonsingular Hermitian matrix; and, hence, $T = W_1^{-1}$. Then, on postmultiplying relations (3.4), in turn, by $M_1^*$, $N_1^*$ and $-A_1^{-1}(a)M_2^*E_1^*$, $A_1^{-1}(b)N_2^*E_1^*$, respectively, and adding, it follows from (2.18), (2.19b), (3.2) and the definition of $E_1$ that the matrix $S$ has the representations:

\[
S = \Theta + E_1(M_2M_1^* + N_2N_1^*)W_1^{-1}, \quad S = \Theta + W_1^{-1}(M_1M_2^* + N_1N_2^*)E_1^*
\]

where

(3.6) \quad \Theta = W_1^{-1}(M_1A_1(a)M_1^* - N_1A_1(b)N_1^*)W_1^{-1}.

As $S - S^* = \Theta + \Omega$, the matrix $S - \frac{1}{2}\Theta - \frac{1}{2}\Omega$ is Hermitian; and, consequently,
\[ H(x)[M_2y(a) + N_2y(b)] + K(x) \int_a^b F_1(\lambda)y \, dt \]

\[ = F_1^*(x)[W_1^{-1}[-M_1A_1(a)y(a) + N_1A_1(b)y(b)] + \frac{1}{2}\Omega[M_1y(a) + N_1y(b)]] \]

\[ + F_1^*(x)[\Gamma + \frac{1}{2}\Omega + \frac{1}{2}\Theta - S] \int_a^b F_1(\lambda)y \, dt \]

for vectors \( y \in C \) satisfying the integro-boundary conditions of (3.1). The invariance property of the adjoint problem, discussed in the previous section, then assures the following result.

**Theorem 3.1.** Every symmetric integro-differential-boundary problem (3.1) is representable in the form

\[ A_1(x)y' + A_0(x)y + F_1^*(x)[W_1^{-1}[-M_1A_1(a)y(a) + N_1A_1(b)y(b)] + \frac{1}{2}\Omega[M_1y(a) + N_1y(b)]] + F_1^*(x)\Psi \int_a^b F_1(\lambda)y \, dt = \lambda B(x)y, \]

(3.7)

\[ M_0y(a) + N_0y(b) = 0, \]

\[ M_1y(a) + N_1y(b) + \int_a^b F_1(\lambda)y \, dt = 0, \]

where \( \Psi \) is a \( \sigma \times \sigma \) constant Hermitian matrix, \( W_1 \) is defined by (3.5) and \( \Omega \) by (3.6), the orthogonality relations (2.19b) and (3.2) hold, and the \( \sigma \) rows of \( F_1(x) \) are linearly independent and the matrices \( A_1(x), A_0(x) \) and \( B(x) \) satisfy (2.19c) on \([a, b]\).

Conversely, a problem (3.7) with the \( \rho \) rows of \([M_0, N_0]\) and the \( \sigma \) rows of \([M_1, N_1]\) constituting \( \rho + \sigma = n \) linearly independent rows satisfying (2.19b) and (3.2), \( \Psi \) a \( \sigma \times \sigma \) constant Hermitian matrix, \( W_1 \) and \( \Omega \) given by (3.5) and (3.6), respectively, and for which relations (2.19c) hold and the \( \sigma \) rows of \( F_1(x) \) are linearly independent on \([a, b]\), is symmetric and coincides with its adjoint problem term-by-term.

Moreover, for a symmetric problem (3.7) satisfying the conditions listed in Theorem 3.1 the rows of the end-point coefficient matrix \([M_0, N_0; M_1, N_1]\) may be orthonormalized, in view of condition (3.2), by premultiplying the two sets of integro-boundary conditions by the unique positive square roots of \( W_0^{-1} \) and \( W_1^{-1} \), respectively. The resulting system may then be said to be in canonical form.

**Corollary.** Every symmetric integro-differential-boundary problem (3.1) is reducible to the form
\[ A_1(x)y' + A_0(x)y + F_1^*(x)[ - M_1 A_1(a)y(a) + N_1 A_1(b)y(b) ] + F_1^*(x)[\Psi + \Lambda] \int_a^b F_1(\tau)y\ d\tau = \lambda B(x)y, \]

\[ M_0 y(a) + N_0 y(b) = 0, \]

\[ M_1 y(a) + N_1 y(b) + \int_a^b F_1(\tau)y\ d\tau = 0, \]

where \[ \Lambda = (1/2)(- M_1 A_1(a) M_1^* + N_1 A_1(b) N_1^*), \]
\[ \Psi \text{ is a } \sigma \times \sigma \text{ constant Hermitian matrix, relations (2.19c) hold and the rows of } F_1(x) \text{ are linearly independent on } [a, b], \]
the rows of the \[ n \times 2n \] matrix \[ [M_0, N_0; M_1, N_1] \]
are orthonormalized in the sense that \[ M_0 M_0^* + N_0 N_0^* = I, M_1 M_1^* + N_1 N_1^* = I, \] and \[ M_0 M_0^* + N_0 N_0^* = 0, \]
and

\[ [M_0, N_0; M_1, N_1] \cdot \text{diag} \{ - A^{-1}(a), A^{-1}(b) \} \cdot [M_0, N_0; M_1, N_1]^* = 0. \]

In particular, if \[ \Lambda = 0 \] for a symmetric problem (3.1), as it does, for example, if \( A_1(x) \) is a constant multiple of a unitary matrix, the forms (3.7) and (3.8) are further reduced.

REFERENCES