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SANOAT VA TEXNIKA SOHALARIDA OLIB BORILAYOTGAN ISLOHOTLAR VA ULARNING NATIJALARI

mahalliy konferensiya materiallari

JILD 2, SON 8
O‘zbekiston, Buxoro

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SANOAT VA TEXNIKA SOHALARIDA OLIB BORILAYOTGAN ISLOHOTLAR VA ULARNING NATIJALARI

MAVZUSIDAGI RESPUBLIKA ILMIY-AMALIY ONLINE KONFERENSIYASI MATERIALLARI TO‘PLAMI

VIII SON

BUXORO-2026

SANOAT VA TEXNIKA SOHALARIDA OLIB BORILAYOTGAN ISLOHOTLAR VA ULARNING NATIJALARI TO‘PLAM

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LYAPUNOV EXPONENTIAL STABILITY OF AN IMPLICIT UPWIND SCHEME FOR A BOUNDARY-CONTROLLED HYPERBOLIC SYSTEM

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Qabul qilindi: 28.09.2026
Ko‘rib chiqildi: 29.09.2026
Tasdiqlandi: 30.09.2026

1. Introduction. For the boundary control problem of a linear symmetric t-hyperbolic system with variable coefficients, a companion thesis constructs an implicit upwind difference scheme that is free of a Courant–Friedrichs–Lewy (CFL) mesh restriction. The present thesis addresses the stability, in the sense of Lyapunov, of the numerical solution of that scheme: a discrete Lyapunov function is constructed, an a priori estimate for it is obtained, and this estimate is shown to imply exponential stability of the discrete solution in the ℓ^2-norm, under a dissipativity condition on the boundary control parameters.

2. The scheme and the discrete Lyapunov function. On the mesh $t^\kappa = \kappa\Delta t$, $x_j = j\Delta x$, the implicit upwind scheme for

$$\frac{\partial \mathbf{v}}{\partial t} + K(x)\frac{\partial \mathbf{v}}{\partial x} + Q(x)\mathbf{v} = 0$$

(1) with boundary conditions $\mathbf{v}^I = s\,\mathbf{v}^{II} + \psi^I(t)$ at $x = 0$ and $\mathbf{v}^{II} = r\,\mathbf{v}^I + \psi^{II}(t)$ at $x = l$ reads

$$(v_i)_j^{\kappa+1} = (v_i)_j^\kappa - (a_i)_j \frac{\Delta t}{\Delta x}\left[(v_i)_j^{\kappa+1} - (v_i)_{j-1}^{\kappa+1}\right] - \Delta t\, q_j (v_i)_j^{\kappa+1}, \quad i \le m,$$

(2)

$$(v_i)_j^{\kappa+1} = (v_i)_j^\kappa - (a_i)_j \frac{\Delta t}{\Delta x}\left[(v_i)_{j+1}^{\kappa+1} - (v_i)_j^{\kappa+1}\right] - \Delta t\, q_j (v_i)_j^{\kappa+1}, \quad i > m,$$

(3) with the discrete boundary conditions $(\mathbf{v}^I)_0^{\kappa+1} = s(\mathbf{v}^{II})_1^{\kappa+1} + (\psi^I)^{\kappa+1}$, $(\mathbf{v}^{II})_j^{\kappa+1} = r(\mathbf{v}^I)_{j-1}^{\kappa+1} + (\psi^{II})^{\kappa+1}$.

For $\nu > 0$ and $\mu_i > 0$, define, as in the continuous theory, the exponential weights

$$e_j^+ = \exp\left(-\Delta x \sum_{q=0}^{j} \frac{\nu}{(a_i)_q}\right), \quad i \le m, \qquad e_j^- = \exp\left(\Delta x \sum_{q=0}^{j} \frac{\nu}{(a_i)_q}\right), \quad i > m,$$

(4) and the discrete Lyapunov function

$$V_i^{\kappa} = \Delta x \sum_{j=1}^{J-1} \frac{\mu_i}{(a_i)_j} e_j^{+} [(v_i)_j^{\kappa}]^2 \ (i \le m), \qquad V_i^{\kappa}$$

$$= \Delta x \sum_{j=1}^{J-1} \frac{\mu_i}{(a_i)_j} e_j^{-} [(v_i)_j^{\kappa}]^2 \ (i > m), \qquad V^{\kappa} = \sum_{i=1}^{n} V_i^{\kappa}.$$

(5)

3. One-step estimate. The key technical step, specific to the implicit scheme, is an a priori estimate for the increment of V_i^{κ} along a single time step, which splits into two cases according to the sign of the zero-order coefficients q_j.

Lemma 1. *Let* $\bar{q} = \max_{i,j} |q_j|$. *For* $i \le m$,

$$\frac{V_i^{\kappa+1} - V_i^{\kappa}}{\Delta t}$$

$$\le \begin{cases} \mu_i \sum_{j=1}^{J-1} e_{j-1}^{+} \{[(v_i)_{j-1}^{\kappa+1}]^2 - [(v_i)_j^{\kappa+1}]^2\}, & \text{if } q_j \ge 0 \ \ \forall i, j, \\ \mu_i \sum_{j=1}^{J-1} e_{j-1}^{+} \{[(v_i)_{j-1}^{\kappa+1}]^2 - [(v_i)_j^{\kappa+1}]^2\} + 2\bar{q}\, V_i^{\kappa+1}, & \text{if } q_j < 0 \ \text{ for some } i, j, \end{cases}$$

(6) *and symmetrically for* $i > m$.

Proof idea. Writing the implicit update (2) in the form $(v_i)_j^{\kappa+1}(1 + \rho_{ij} + \Delta t\, q_j) = (v_i)_j^{\kappa} + \rho_{ij}(v_i)_{j-1}^{\kappa+1}$, $\rho_{ij} = (a_i)_j \Delta t / \Delta x$, and multiplying by $2(v_i)_j^{\kappa+1}$, one isolates $[(v_i)_j^{\kappa+1}]^2 - [(v_i)_j^{\kappa}]^2$ as a combination of $\rho_{ij}\{[(v_i)_{j-1}^{\kappa+1}]^2 - [(v_i)_j^{\kappa+1}]^2\}$, a nonpositive quadratic remainder (using $2ab \le a^2 + b^2$), and the term $-2\Delta t\, q_j [(v_i)_j^{\kappa+1}]^2$. If $q_j \ge 0$ this last term is nonpositive and may be dropped, giving the first case of (6); if $q_j < 0$ it is bounded by $2\Delta t\, \bar{q}\, [(v_i)_j^{\kappa+1}]^2$, which, after multiplying by the weight $\mu_i e_{j-1}^{+} / \Delta t$ and summing over j, produces the extra term $2\bar{q}\, V_i^{\kappa+1}$ in the second case. ■

Lemma 2 (summation by parts). *For* $i \le m$,

$$\sum_{j=1}^{J-1} e_{j-1}^{+}\left\{[(v_i)_{j-1}^{\kappa+1}]^2-[(v_i)_{j}^{\kappa+1}]^2\right\}$$

$$= e_0^{+}[(v_i)_0^{\kappa+1}]^2 - e_{J-2}^{+}[(v_i)_{J-1}^{\kappa+1}]^2 + \sum_{k=1}^{J-2}(e_k^{+}-e_{k-1}^{+})\,[(v_i)_k^{\kappa+1}]^2,$$

(7) *with* $e_k^{+}-e_{k-1}^{+}\le 0$*; the symmetric identity holds for* $i>m$.

Combining Lemmas 1–2, each $V_i^{\kappa+1}-V_i^{\kappa}$ is bounded by a boundary term in $(v_i)_0^{\kappa+1}$, $(v_i)_{J-1}^{\kappa+1}$, a nonpositive interior sum carrying the factor ν (through $e_k^{+}-e_{k-1}^{+}$), and, when q_j changes sign, a term proportional to $V_i^{\kappa+1}$ itself.

4. Boundary dissipativity and the main theorem. As in the continuous and the explicit discrete theory, dissipativity of the boundary control parameters (s,r) is measured through

$$\rho_2(R)=(1+\gamma)\inf_{D}\parallel DRD^{-1}\parallel_2, \qquad R=\begin{pmatrix}0 & s\\ r & 0\end{pmatrix},$$

(8) the infimum taken over positive diagonal matrices $D=\mathrm{diag}(d_1,\dots,d_n)$, $\gamma>0$. Substituting the discrete boundary conditions into the boundary terms arising from Lemma 2 (summed over all i) produces a quadratic form in $(\mathbf{v}^{I})_{J-1}^{\kappa+1}$, $(\mathbf{v}^{II})_0^{\kappa+1}$ whose negative definiteness, for an appropriate choice of the weights μ_i, is equivalent to $\rho_2(R)<1$, exactly as in the continuous case.

Theorem 2.1. *Let* $T>0$ *and let the discrete Lyapunov function* V^{κ} *be defined by (4)–(5). If the boundary control parameters* (s,r) *satisfy* $\rho_2(R)<1$*, then the numerical solution* $\mathbf{v}_j^{\kappa}$ *of the implicit scheme (2)–(3) with the discrete boundary conditions is exponentially stable in the discrete* ℓ^2*-norm: there exist constants* $\eta>0$, $c>0$ *such that*

$$\Delta x\sum_{j}|\,\mathbf{v}_j^{\kappa}|^2\le c\,e^{-\eta t^{\kappa}}\,\Delta x\sum_{j}|\,\mathbf{v}_j^{0}|^2, \qquad \kappa=1,\dots,K.$$

(9)

Proof outline. Lemmas 1–2 and the boundary dissipativity estimate combine, for $\nu>0$ sufficiently small, into a one-step inequality of the form $V^{\kappa+1}\le\alpha V^{\kappa}+\beta$, with $0<\alpha<1$ and β controlled by the control inputs ψ^{I},ψ^{II} (in particular $\beta=0$ in the unforced case $\psi^{I}\equiv\psi^{II}\equiv 0$). Iterating this inequality and using the discrete analogue of Gronwall's lemma yields $V^{\kappa}\le\alpha^{\kappa}V^{0}+\beta(1-\alpha^{\kappa})/(1-\alpha)$. Since $\alpha=1-O(\nu\Delta t)$, this gives $V^{\kappa}\le c_0e^{-\eta t^{\kappa}}V^{0}$ for $\eta>0$ proportional to ν, and the

equivalence of V^{κ} with the discrete ℓ^2-norm (uniform in $\Delta x, \Delta t$, by the boundedness of the weights (4)) yields (9). ■

5. Conclusion. For the implicit upwind scheme approximating a linear symmetric t-hyperbolic boundary control problem, a discrete Lyapunov function was constructed and an a priori one-step estimate for it was established, with an explicit treatment of the sign of the zero-order coefficients q_j. This estimate, combined with the dissipativity condition $\rho_2(R) < 1$ on the boundary control parameters, yields exponential stability of the numerical solution in the discrete ℓ^2-norm (Theorem 2.1), extending to the implicit, CFL-free discretization the exponential stability theory previously established for the explicit scheme of the uncontrolled problem.

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