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STABILITY OF FINITE DIFFERENCE MODELS  
CONTAINING TWO BOUNDARIES OR INTERFACES

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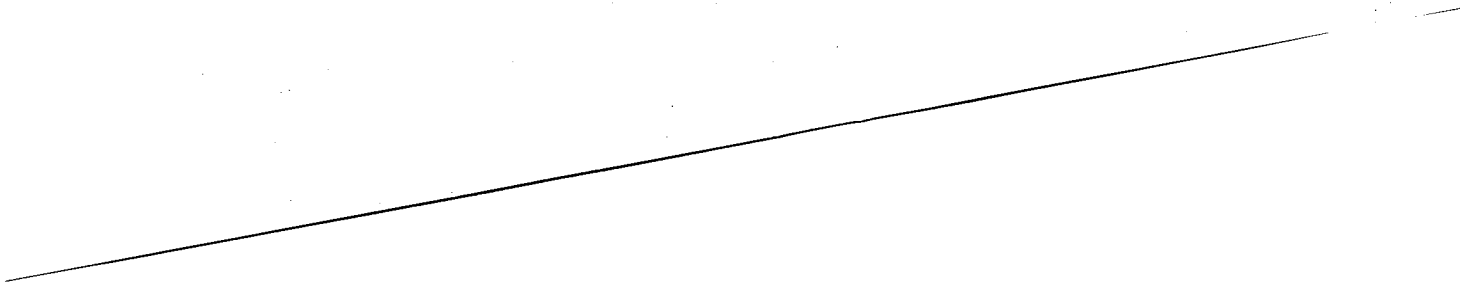
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**STABILITY OF FINITE DIFFERENCE MODELS  
CONTAINING TWO BOUNDARIES OR INTERFACES**

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**ABSTRACT**

It is known that the stability of finite difference models of hyperbolic initial boundary value problems is connected with the propagation and reflection of parasitic waves. Here the waves point of view is applied to models containing two boundaries or interfaces, where repeated reflection of trapped wave packets is a potential new source of instability. Our analysis accounts for various known instability phenomena in a unified way and leads to several new results, three of which are as follows. (1) Dissipativity does not ensure stability when three or more formulas are concatenated at a boundary or internal interface. (2) Algebraic "GKS instabilities" can be converted by a second boundary to exponential instabilities only when an infinite numerical reflection coefficient is present. (3) "GKS-stability" and "P-stability" can be established in certain problems by showing that all numerical reflection coefficients have modulus less than 1.

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## Notation

$j, n$	space, time index
$h, k$	space, time step size
$\lambda = k/h$	mesh ratio
$u(x,t), v_j^n$	continuous, discrete solution vector
$N$	dimension of $u, v$
$\xi, \omega$	wave number, frequency
$C(\xi, \omega)$	group velocity
$z$	temporal amplification factor
$\kappa, \mu$	rightgoing, leftgoing spatial amplification factor
$\ell, r$	no. of pts. to the left, right of center in stencil
$R = N\ell, L = Nr$	no. of rightgoing, leftgoing numerical wave modes
$Q, \bar{Q}$	difference model for i.v.p., i.b.v.p.
$A(z)$	reflection matrix function at boundary
const	positive constant, different each time

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## 0. INTRODUCTION

Hyperbolic systems of partial differential equations admit solutions which behave locally like waves moving along characteristics. When such a system is modeled numerically by finite differences or finite elements, the result is a dispersive medium that may admit additional parasitic wave modes with wavelengths on the scale of the discretization. Energy associated with these parasitic waves travels at a group velocity that is unrelated to the characteristics of the original system [25], [30]. However the behavior of such waves has a decisive effect on stability.

For finite difference models of linear hyperbolic problems with a single spatial boundary, a stability theory was developed around 1970 by Kreiss, Osher, and others [10], [18]. In earlier papers we have shown that this theory can be naturally stated in terms of dispersive wave propagation [26], [27]. To summarize: if a boundary with homogeneous boundary conditions can emit a radiated wave in the absence of any incident waves, i.e., a wave with group velocity pointing into the interior of the domain, then it is unstable. If it has an infinite reflection coefficient for waves at some frequency, a stronger condition, then it is more severely unstable.

This paper applies wave propagation ideas to investigate stability for one-dimensional linear finite difference models with two or more boundaries or internal interfaces. The most basic example of such a model is a discrete approximation to an equation whose spatial domain is an interval such as  $[0,1]$ . Another example is a model of a problem featuring discontinuous coefficients, e.g. wave propagation in a discontinuously stratified medium [4]. A third is a numerical scheme employing local mesh refinement to improve accuracy, in which various interfaces between fine and coarse grids will be

present [2], [5]. A fourth is any model with a composite numerical boundary or interface, such as a fourth-order difference model on  $[0, \infty)$  that has a five-point stencil, and which therefore requires one numerical boundary condition at  $j = 0$  and another at  $j = 1$  [15]. Such a model can be viewed as containing two interfaces separated by a single grid point, and we will show that this view may be useful for stability analysis.

Any multi-interface model potentially admits trapped numerical waves that reflect back and forth repeatedly from one interface to another. If the reflections cause amplification, this can lead to unbounded growth of numerical solutions. The factors that control this are: magnitude of the reflection coefficients, which is the source of growth; dissipation of waves as they travel between interfaces, which is a source of attenuation; and travel time between interfaces, which determines how frequently any reflection circuit that causes growth is repeated. All of the arguments of this paper consist of working out consequences of various combinations of these factors that may be of practical interest.

In particular we investigate two kinds of stability. First, "stability" or "Lax-Richtmyer stability" refers to the usual Lax-Richtmyer definition for time-dependent finite difference models, or to variants thereof such as "GKS-stability" (Defn. 3.3 in the well-known paper by Gustafsson, Kreiss, and Sundström [10]). A difference model that is stable in this sense may admit solutions that grow with time, provided that the growth does not get worse as the mesh is refined. This is what is needed to ensure convergence as the mesh size approaches zero to the correct solution of the time-dependent differential equation, for each fixed time  $t$ . On the other hand to be "p-stable" [1], a model must admit no growing solutions at all. (See Section 3

for the precise definition. Such a model is also sometimes called "time-stable" [29].) Although the theory here is not as well developed, such a condition is needed if a time-dependent difference model is to be used to obtain steady-state solutions, as is common in computational aerodynamics. As a rule of thumb, we will show that P-instability is very often associated with reflection coefficients greater than 1 in magnitude, and Lax-Richtmyer instability with reflections coefficients that are infinite.

Section 1 reviews stability theory for one-boundary difference models (Prop. 1). Section 2 investigates interfaces separated by a fixed number of grid points  $\Delta j$  as the mesh is refined, as in the fourth-order boundary condition mentioned above. Here the travel times go to zero with the mesh spacing, with the effect that finite reflection coefficients greater than 1 can cause catastrophic unstable growth, regardless of dissipation (Props. 3, 4, 4'). Conversely, reflection coefficients smaller than 1 ensure stability (Prop. 5). Section 3 considers interfaces separated by a fixed distance  $\Delta x$  as the mesh is refined, as in the problem on  $[0,1]$  mentioned above. Here the travel times are independent of mesh spacing, so large finite reflection coefficients can cause P-instability (Prop. 7) but not Lax-Richtmyer instability (Prop. 6). In this context multiple reflections may convert the weak instability of a single interface to a catastrophic instability (Prop. 8), but only if the unstable interface is of the sort with an infinite reflection coefficient (Prop. 9). In contrast to the fixed- $\Delta j$  case, dissipation now prevents all kinds of solution growth (Prop. 10), and so again do reflection coefficients less than 1 (Prop. 11).

For convenience of reference, here is a list of the explicit examples presented here to illustrate various points. The symbol A indicates the

modulus of a reflection coefficient, and  $S_n$  the solution norm at time step  $n$ . These quantities will be made more precise later on.

1. Algebraically unstable one-boundary model (one boundary,  $A = \infty$ ,  $S_n \sim \text{const}^n$ ).
2. Exponentially unstable concatenation of three stable dissipative formulas (fixed- $\Delta j$ ,  $A > 1$ ,  $S_n \sim \text{const}^n$ ).
3. P-stability guaranteed by reflection coefficients less than 1 (fixed- $\Delta j$  or  $\Delta x$ ,  $A < 1$ ,  $S_n \sim \text{const}$ ).
4. P-instability caused by reflection coefficients greater than 1 (fixed- $\Delta x$ ,  $A > 1$ ,  $S_n \sim \text{const}^t$ ).
5. Exponential instability caused by interaction of two algebraically unstable boundaries (fixed- $\Delta x$ ,  $A = \infty$ ,  $S_n \sim (\Delta j)^{\text{const } t}$ ).

The reader may be disappointed at the artificiality of some of these examples, especially (2) and (3), and he may wonder how helpful wave reflection ideas can be in practice for the design of difference schemes. A full answer to this question will have to await further experience. Nevertheless there is no doubt that the instability mechanisms described here are real and deserve to be understood. At present, virtually no difference models have been shown to be stable of the sort that contain multiple interfaces at various points, such as might appear in adaptive mesh refinement. Perhaps the ideas here, such as Prop. 5, can help bring about a change in this situation.

Much of the material in this paper can be found in Section 6 of the author's Ph.D. dissertation [24]. For some numerical illustrations, see [28].

For a different analysis of stability for two-boundary problems that is closely related to the present one, see the report [8] by Giles and Thompkins, which is mainly concerned with P-stability. Giles and Thompkins consider parasitic wave propagation for models with variable as well as constant coefficients.

The phenomenon of instability caused by trapped wave packets can also occur in two-dimensional problems when the domain contains a corner. Osher has given examples of hyperbolic systems (not difference models) in corners that are ill-posed because of trapped waves [19], while Sarason and Smoller have shown that for a  $2 \times 2$  strictly hyperbolic system such as the second-order wave equation, this cannot happen [21]. But trapped numerical waves may render a finite difference model of even the latter sort unstable. The principles involved are precisely those of this paper, but we will discuss corners elsewhere.

The reader interested in getting to the main ideas quickly may find it possible to turn directly to Section 2.

## 1. REVIEW OF WAVE PROPAGATION AND STABILITY FOR ONE-BOUNDARY DIFFERENCE MODELS

Consider a linear first-order hyperbolic system of differential equations

$$u_t = Au_x \tag{1.1}$$

with initial data

$$u(x,0) = f(x). \tag{1.2}$$

Here  $u(x,t)$  and  $f(x)$  are  $N$ -vectors,  $A$  is a constant  $N \times N$  matrix, and the spatial domain is  $\mathbb{R}$ . The statement that (1.1) is hyperbolic means that  $A$  has real eigenvalues  $\{\mu_\nu\}$ ,  $1 \leq \nu \leq N$ , and a complete set of associated eigenvectors  $\{U_\nu\}$ . It follows that if  $\xi \in \mathbb{R}$  is an arbitrary wave number, then (1.1) admits  $N$  linearly independent solutions of the form  $u(x,t) = U \exp(i(\omega t + \xi x))$ , namely the waves

$$u(x,t) = U_\nu e^{i(\omega_\nu(\xi)t + \xi x)} \quad (1.3)$$

with  $\omega_\nu(\xi) = \mu_\nu \xi$ .  $\omega_\nu$  is called the frequency of (1.3), and the  $N$ -valued linear function  $\omega = \omega(\xi)$  is the dispersion relation for (1.1). Each wave (1.3) propagates uniformly with no change in shape at the velocity  $-\mu_\nu$ , hence leftward or rightward depending on whether  $\mu_\nu$  is positive or negative, respectively.

Since the vectors  $U_\nu$  span  $\mathbb{R}^N$ , any  $f \in L^2(\mathbb{R}^N)$  can be written as a Fourier integral with respect to  $\xi$  of waves (1.3). It follows by Parseval's theorem that  $\|u(\cdot, t)\|$  is constant with respect to  $t$ ; a fortiori, for any fixed  $t$  one has

$$\|u(\cdot, t)\| \leq \text{const } \|f\|, \quad (1.4)$$

which is to say, (1.1) - (1.2) is well posed in  $L^2$ . Related well-posedness bounds continue to hold under reasonable assumptions if (1.1) is given a zeroth-order term  $Bu$ , an inhomogeneous term  $F(x,t)$ , or variable coefficients, although in these circumstances some growth at a bounded rate in  $t$  must be permitted. For simplicity we will ignore these possibilities.

Let  $u$  be approximated by a vector grid function  $v_j^n = v(jh, nk) \approx u(jh, nk)$ , where  $k$  is a time step and  $h$  is a space step.  $\{v_j^n\}$  will be determined iteratively as the solution of an  $s+2$ -level finite difference formula

$$Q_{-1} v^{n+1} = \sum_{\sigma=0}^s Q_{\sigma} v^{n-\sigma}, \quad (1.5)$$

where each  $Q_{\sigma}$  is a spatial finite difference operator with constant matrix coefficients of dimension  $N \times N$ . Let  $Q$  be a name for (1.5). As with the differential equation, one can show that  $Q$  admits solutions

$$v_j^n = V e^{i(\omega t + \xi x)}, \quad x = jh, \quad t = nk, \quad V \in \mathbb{R}^N. \quad (1.6)$$

For each  $\xi \in \mathbb{R}$ , in fact, it permits in general not  $N$  but  $(s+1)N$  distinct values of  $\omega$ , whose relation to  $\xi$  constitutes the dispersion relation for (1.5). These values depend nonlinearly on  $\xi$ , and they are not necessarily real. A solution with  $\xi \in \mathbb{R}$  and  $\text{Im}\omega > 0$  decays with  $t$ , but a solution with  $\xi \in \mathbb{R}$  and  $\text{Im}\omega < 0$  grows at the rate  $e^{|\text{Im}\omega|t} = \text{const}^n$ , and if  $Q$  admits a solution of this kind, it is unstable. On the other hand if there are no such growing modes, and if any modes with  $\xi, \omega \in \mathbb{R}$  are nondefective in a sense we will not go into, then  $Q$  is stable. Thus stability for a constant coefficient finite difference model on an unbounded domain can be investigated by a fairly straightforward process of Fourier analysis. For details, see [20].

Let  $Q$  be stable and admit a solution (1.6) with  $\xi, \omega \in \mathbb{R}$ . It can be shown that the dispersion relation for (1.5) determines a function  $\tilde{\omega} = \tilde{\omega}(\tilde{\xi})$  for  $\tilde{\xi}, \tilde{\omega}$  in a neighborhood of  $\xi, \omega$  [27, Lemma 3.2], and that the energy

associated with the wave (1.6) propagates at the group velocity

$$C(\xi, \omega) = - \frac{d\tilde{\omega}}{d\tilde{\xi}} (\xi, \omega). \quad (1.7)$$

The precise meaning of this statement is asymptotic: if  $Q$  is given initial data

$$f_j^\sigma = \phi(x-Ct) V e^{i(\omega t + \xi x)} \quad 0 \leq \sigma \leq s, \quad t = \sigma k, \quad x = jh$$

for some smooth function  $\phi$ , then the solution at a later time will be

$$v_j^n \approx \phi(x-Ct) V e^{i(\omega t + \xi x)}$$

with the equality becoming more exact as  $\phi$  is made smoother. See for example Lemma 5.1 of [27].

Example 1. As an example, consider the leap frog (LF) model

$$v_j^{n+1} = v_j^{n-1} + \lambda (v_{j+1}^n - v_{j-1}^n), \quad \lambda = \frac{k}{h} = \text{const} \quad (1.8)$$

of  $u_t = u_x$ . By inserting  $v(x, t) = e^{i(\omega t + \xi x)}$ , one finds that the dispersion relation is

$$\sin \omega k = \lambda \sin \xi h. \quad (1.9)$$

Differentiation leads to the group velocity formula

$$C(\xi, \omega) = - \frac{\cos \xi h}{\cos \omega k}. \quad (1.10)$$



Thus a well-resolved wave, i.e. one with  $\xi h, \omega k \approx 0$ , propagates under LF with group velocity  $C \approx -1$ . On the other hand LF also admits many waves with  $\xi h$  or  $\omega k$  not small. The extreme cases are the "parasitic" solutions  $(\xi, \omega) = (\pi/h, 0)$ ,  $(0, \pi/k)$ , and  $(\pi/h, \pi/k)$ , which by (1.10) have group velocities  $+1$ ,  $+1$ , and  $-1$ , respectively. For the first two of these, the sign of  $C$  reveals that energy propagates in the physically wrong direction. In fact for each sufficiently small frequency  $\omega \in \mathbb{R}$ , (1.9) gives two distinct wave numbers  $\xi$  in the fundamental range  $[-\pi/h, \pi/h]$ , and by (1.10), one of the corresponding waves propagates leftwards and the other propagates rightwards. See [25] or [30] for illustrations. //

Returning to the general model  $Q$  of (1.5), let us change the notation and rewrite (1.6) in the more convenient form

$$v_j^n = V \kappa^j z^n \quad \kappa, z \in \mathbb{C} - \{0\} \quad (1.11)$$

where  $\kappa = e^{i\xi h}$  and  $z = e^{i\omega k}$ . (For full generality one must permit a further multiplicative factor  $j^\delta$  to represent certain defective modes. Such modes are rarely important in practice, however, so in all of what follows we assume  $\delta = 0$ , although the results remain valid in the general situation. The reader is referred to [27] for more complete details.) A solution (1.11) with  $|\kappa| = |z| = 1$  and  $C \leq 0$  (resp.  $> 0$ ) will be called leftgoing (resp. rightgoing). For obvious geometric reasons it also makes sense to say that a solution with  $|z| > 1$  is leftgoing if  $|\kappa| > 1$  and rightgoing if  $|\kappa| < 1$ . It can be shown under reasonable assumptions (see [10]) that for any  $z$  with  $|z| > 1$ ,  $Q$  admits a family of  $R = N\ell$  linearly independent rightgoing and  $L = Nr$  linearly independent leftgoing solutions (1.11), where  $\ell$  and  $r$

denote the numbers of grid points to the left and right of center, respectively, covered by the stencil of  $Q$  [27, Sec. 3]. Therefore, the general solution to (1.5) of the form  $v_j^n = z^n \phi_j$  is a linear combination

$$v_j^n = z^n \sum_{m=1}^{R+L} \alpha_m V_m \kappa_m^j .$$

If we relabel  $\alpha$ ,  $V$ , and  $\kappa$  by  $\beta$ ,  $W$ , and  $\mu$  for leftgoing components, this becomes

$$v_j^n = z^n \sum_{m=1}^R \alpha_m V_m \kappa_m^j + z^n \sum_{m=1}^L \beta_m W_m \mu_m^j . \quad (1.12)$$

(RIGHTGOING)                      (LEFTGOING)

We emphasize that the leftgoing and rightgoing waves in this sum have very little to do with the waves admitted by the original equation (1.1).

Let a lefthand boundary be introduced at  $x = 0$ , so that the spatial domain becomes  $\mathbb{R}^+$  and  $j$  is restricted to  $j \geq 0$ . Now (1.1) must be supplemented by as many additional scalar boundary conditions as there are inflowing characteristics at  $x = 0$ , and if this done in the natural way, well-posedness is guaranteed [13]. But we pass over these details and consider the finite difference model. Regardless of the characteristics of (1.1), (1.5) will have to be supplemented by  $R = N\ell$  additional boundary conditions, one for each rightgoing numerical solution component. For simplicity we take these to be homogeneous and of the form

$$v_j^{n+1} = \sum_{\sigma=-1}^{M_1} \sum_{i=0}^{M_2} \gamma_{i\sigma} v_i^{n-\sigma} \quad 0 \leq j \leq \ell-1 \quad (1.13)$$

for some integers  $M_1$  and  $M_2$  and  $N \times N$  matrices  $\gamma_{i\sigma}$ . Let  $\bar{Q}$  be a name for the initial boundary value problem model (1.5), (1.13).

In practice it can easily happen that  $\bar{Q}$  is unstable. A theory of such instability was developed a decade ago by Kreiss, Osher, and others, and described at length in the well-known paper [10] by Gustafsson, Kreiss, and Sundström — henceforth "GKS". In [26] and [27] the Kreiss/Osher theory has been given the following interpretation. If  $|z| > 1$  is fixed, then the general superposition (1.12) of leftgoing and rightgoing waves does not satisfy (1.13), and hence is not a solution to  $\bar{Q}$ . Instead, (1.13) can be thought of as a set of  $R = N^l$  reflection conditions relating rightgoing to leftgoing waves at the boundary. These conditions are obtained by substituting (1.12) in (1.13) and then collecting terms in  $\alpha_m$  and  $\beta_m$ , so that one gets

$$E(z) \begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_R \end{bmatrix} = D(z) \begin{bmatrix} \beta_1 \\ \vdots \\ \beta_L \end{bmatrix} \quad (1.14)$$

for some  $R \times R$  matrix  $E(z)$  and  $R \times L$  matrix  $D(z)$ . For most  $z$ ,  $E(z)$  will be nonsingular, and (1.14) determines the reflected wave coefficients as a bounded function of the incident ones. If we write  $A = E^{-1} D$ , so that  $A(z)$  is the  $R \times L$  reflection matrix for the given boundary conditions, then this function has the form

$$\alpha = A(z)\beta = [E(z)]^{-1} D(z)\beta. \quad (1.15)$$

(This  $A(z)$  has nothing to do with the coefficient matrix of (1.1).) However, it may happen that for some  $|z_0| > 1$ ,  $E(z_0)$  is singular, and in this case (1.14) permits a solution consisting of rightgoing waves in the absence of leftgoing waves. This will cause instability. If in this situation  $A(z)$  is unbounded as  $z \rightarrow z_0$ , then an infinite reflection coefficient exists at  $z_0$ , and the instability will be particularly severe [27].

Thus the Kreiss/Osher theory leads to the following "GKS stability theorem":

**PROPOSITION 1** [10, 27]. The initial boundary value problem model  $\bar{Q}$  is GKS-unstable if and only if  $E(z)$  is singular for some  $|z| > 1$ . Equivalently, it is GKS-unstable if and only if for some  $|z| > 1$  it admits a nonzero solution  $v_j^n = z^n \phi_j$  (1.12) consisting entirely of rightgoing wave components.

Proof. See [27] for a precise statement and proof. ■

The notion of "GKS-stability" employed in this result is a fairly complicated one given as Defn. 3.3 in [10]. See [27] for a discussion of its meaning. For the remainder of this paper "stable" means "GKS-stable", except where otherwise stated.

Example 1, continued. To return to the previous example, suppose LF is applied on  $x > 0$  with the numerical boundary condition

$$v_0^{n+1} = v_1^{n+1}. \quad (1.16)$$

In  $\kappa, z$  notation, the dispersion relation (1.9) and group velocity (1.10) for LF are

$$z - \frac{1}{z} = \lambda \left( \kappa - \frac{1}{\kappa} \right), \quad C = - \frac{\kappa + 1/\kappa}{z + 1/z}, \quad (1.17)$$

and (1.16) imposes the additional condition  $\kappa = 1$ . One sees immediately that the wave  $(\kappa, z) = (1, -1)$ , i.e.,  $v_j^n = (-1)^n$ , satisfies both the interior formula and the boundary condition and has  $C > 0$ . Therefore by Prop. 1 the model (1.8), (1.16) is unstable. By contrast the condition  $v_0^{n+1} = v_1^n$  is satisfied by no rightgoing solutions to LF, so with this boundary condition LF would be stable.

This example is one of those with an infinite reflection coefficient. To see this, note that for each  $|z| > 1$ , (1.17) gives two values of  $\kappa$  related by  $\kappa_2 = -1/\kappa_1$ . Let these be denoted by  $\kappa$  and  $\mu$ , where  $\kappa$  is the "rightgoing" value with  $\text{Re} \kappa \text{Re} z < 0$  and  $|\kappa| < 1$ , for which  $C > 0$  if  $|\kappa| = 1$ , and  $\mu$  is the "leftgoing" one with  $\text{Re} \kappa \text{Re} z > 0$  and  $|\kappa| > 1$ . Then for this problem the superposition (1.12) takes the form  $v_j^n = \alpha \mu^j + \beta \kappa^j$ . To calculate the reflection coefficient we substitute this in (1.16) and obtain  $\alpha + \beta = \alpha \mu + \beta \kappa$ , that is,  $\beta = A\alpha$  with

$$A(z) = - \frac{1 - \mu}{1 - \kappa}. \quad (1.18)$$

This quotient becomes infinite when  $z = -1$ ,  $\kappa = 1$ ,  $\mu = -1$ .

The unstable behavior of this difference model is illustrated in Figs. 4.1 - 4.2 and Figs. 5.1 - 5.4 of [24] and in Figs. 3, 4 of [27]. //

## 2. TWO INTERFACES SEPARATED BY A FIXED NUMBER OF GRID POINTS $\Delta j$

The stability result of Prop. 1 is illustrated in Fig. 1. If a set of numerical waves reflects at a boundary with a gain in amplitude, as in Fig. 1a, this does not constitute instability. It may force the constant in a discrete estimate analogous to (1.4) to be large, but it does not preclude the existence of such an estimate. On the other hand if the boundary can produce radiated energy in the presence of no incident energy at all, as in Fig. 1b, then it is unstable.



(a) stable

(b) unstable

**Figure 1.** Stable and unstable solutions  $z^n \phi_j$  at a lefthand boundary.

Suppose now that  $\bar{Q}$  is a model containing not a boundary but an internal interface of some kind separating two difference schemes  $Q_-$  and  $Q_+$  (possibly identical). The interface might be a complicated structure extending over several grid points, or it might be simply an abrupt change of coefficient, of difference formula, or of mesh size. It is plausible that the picture should change to that of Fig. 2:  $\bar{Q}$  is unstable if and only if it permits a solution  $z^n \phi_j$  that is outgoing from the interface on both

sides. This conclusion can be derived rigorously from Prop. 1 by folding the interface problem into an initial boundary value problem for a system of equations of twice the original size [3], [5], [6], [16], [24].



**Figure 2.** Stable and unstable solutions  $z^n \phi_j$  at an internal interface.

Reflection equations for an internal interface analogous to (1.14) - (1.15) for a boundary can be obtained by the same folding idea. For each  $|z| > 1$ , there are  $R^- + L^+$  linearly independent waves that may be incident at the interface from both sides, and  $L^- + R^+$  that may be radiated. The full reflection equation is the linear system describing how the coefficients of these wave components are related,

$$E(z) \begin{bmatrix} \beta_1^- \\ \vdots \\ \beta_{L^-}^- \\ \alpha_1^+ \\ \vdots \\ \alpha_{R^+}^+ \\ R^+ \end{bmatrix} = D(z) \begin{bmatrix} \alpha_1^- \\ \vdots \\ \alpha_{R^-}^- \\ \beta_1^+ \\ \vdots \\ \beta_{L^+}^+ \\ L^+ \end{bmatrix}, \tag{2.1}$$

where  $E$  and  $D$  are matrix functions of dimensions  $(L^- + R^+) \times (L^- + R^+)$  and  $(L^- + R^+) \times (R^- + L^+)$  (cf. (1.14)). However, in this paper we will only need the response of an interface on one side to a wave incident on that side. The corresponding reflection equation is the projection of (2.1) onto a one-sided domain and range. In the case of incidence on the right, for example, it has the form

$$E(z) \begin{bmatrix} \alpha_1^+ \\ \vdots \\ \alpha_{R^+}^+ \end{bmatrix} = D(z) \begin{bmatrix} \beta_1^+ \\ \vdots \\ \beta_{L^+}^+ \end{bmatrix}, \quad (2.2)$$

where  $E$  is  $R^+ \times R^+$  and  $D$  is  $R^+ \times L^+$ . When  $E(z)$  is nonsingular, (2.2) can be solved to yield an equation analogous to (1.15),

$$\alpha^+ = A(z)\beta^+, \quad (2.3)$$

where  $A$  is  $R^+ \times L^+$ . Note that although wave modes on the left of the interface do not appear in (2.3), the projection process by which this equation is obtained imposes the condition that the wave energy on the left is nonzero in the leftgoing components only. In other words (2.2) - (2.3) describes the response of the interface to energy incident on the right.

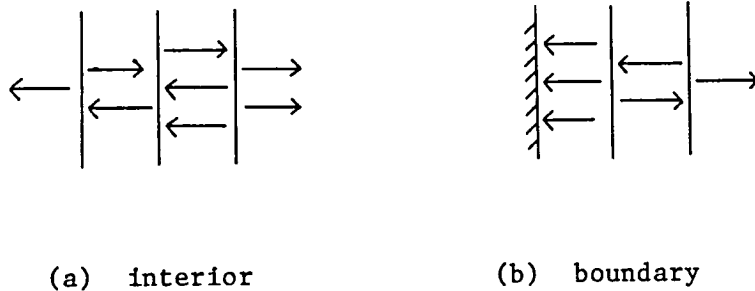
Now consider a finite difference model  $\bar{Q}$  with  $p$  interfaces located at grid points  $j = j_1, \dots, j_p$ , and write  $\Delta j = j_p - j_1$ . (To be precise, each  $j_v$  is a half-integer, with one difference formula applied on  $j_{v-1} < j < j_v$  and another on  $j_v < j < j_{v+1}$ ,  $j \in \mathbb{Z}$ .) In this section the indices  $j_v$  are to be kept fixed as  $h, k \rightarrow 0$ , and we recognize this assumption by calling  $\bar{Q}$



a model of "fixed- $\Delta_j$ " type. As mentioned in the Introduction, a fixed- $\Delta_j$  problem might come up in the analysis of adaptive mesh-refinement procedures, or with any boundary or interface discretization that involves more than two distinct difference formulas. We obtain the following stability criterion:

**PROPOSITION 2.** A fixed- $\Delta_j$  multi-interface difference model is unstable if and only if for some  $|z| > 1$  it admits a nonzero solution  $z^n \phi_j$  containing only leftgoing waves to the left and rightgoing waves to the right of all interfaces.

Proof. The situation is illustrated in Fig. 3. For a proof, one can relabel the grid points so that the interval from  $j_1$  to  $j_p$  becomes one complicated interface separating the two regions  $j < j_1$  and  $j > j_p$ . Then the folding argument mentioned above for a single interface applies. ■



**Figure 3.** Unstable multi-interface solutions  $z^n \phi_j$  at an interior interface and at a boundary.

Remark. In the case of an initial boundary value problem with a boundary at the left, say, the region to the left of the interfaces in Prop. 2 becomes

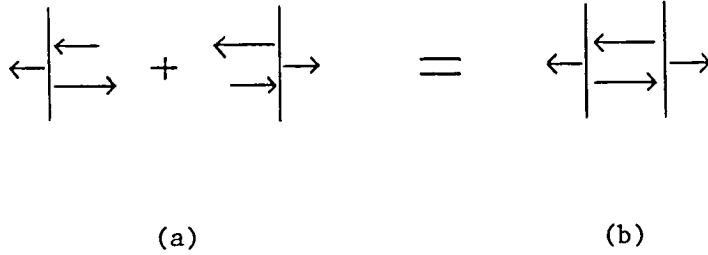
finite in extent (or possibly empty, depending on labeling), so in principle one should not restrict the search for unstable modes to solutions that are leftgoing there. But in this region the difference formula is necessarily one-sided, which implies under the usual assumptions that it admits leftgoing waves only for  $|z| > 1$ . Therefore the change is vacuous.

From the wave propagation point of view the following result should now be unsurprising.

**PROPOSITION 3.** For the stability of a fixed- $\Delta_j$  multi-interface model, it is not sufficient that the individual interfaces be stable.

Remark. Stability of the individual interfaces is presumably not necessary, either.

Proof. The proof consists of exhibiting Example 2, below, but the idea behind it is indicated in Fig. 4. Imagine two interfaces at which waves can reflect with a reflection coefficient greater than 1. When these are placed together, it might happen that the reflected wave from each interface serves to stimulate the reflected wave from the other. A process of reflection back and forth will then ensue in which at each circuit, the amplitude grows by a factor  $\text{const} > 1$ . Since one circuit takes only a fixed number of time steps, this process will cause growth at a rate  $\|v^n\| = \text{const}^n$ , which is an explosive instability. ■



**Figure 4.** The concatenation of stable interfaces may be unstable.

Example 2. Let  $u_t = u_x$  on  $x > 0$  be modeled by an "interior" formula for  $j \geq 2$  combined with additional boundary formulas at  $j = 0$  and  $j = 1$ . The interior formula is an upstream difference with some added dissipation:

$$v_j^{n+1} = v_j^n + \lambda(v_{j+1}^n - v_j^n) + \frac{9\lambda}{8}(v_{j+1}^n - 2v_j^n + v_{j-1}^n) \quad j \geq 2. \quad (2.4)$$

The formula at  $j = 0$  is a linear combination of upstream differences:

$$v_0^{n+1} = v_0^n + \frac{\lambda}{8} \left( \frac{v_2^n - v_0^n}{2} \right) + \frac{7\lambda}{8} \left( \frac{v_3^n - v_0^n}{3} \right). \quad (2.5)$$

At  $j = 1$  we use a leapfrog formula with some added dissipation:

$$v_1^{n+1} = v_1^{n-1} + \lambda(v_2^n - v_0^n) + \epsilon(v_2^{n+1} - 2v_1^{n+1} + v_0^{n+1}). \quad (2.6)$$

It is verified in Sec. 6.3 of [24] that if  $\lambda = \frac{1}{8}$  and  $\epsilon = 1036/83205$ , then (2.4) - (2.6) is exponentially unstable, admitting a solution  $v_j^n = z^n \phi_j$  with  $z = 129/128$ . The eigensolution  $\phi$  has the form  $(1/4, 1, 1/2, 1/4, 1/8, \dots)$ , and can be viewed as the superposition of leftgoing and rightgoing waves represented in Fig. 3b. A numerical experiment confirms that (2.4) - (2.6) is highly unstable and blows up like  $(129/128)^n$  [24]. //

We have chosen such an unwieldy example because it is contrived to have a special additional property: all of the formulas (2.4) - (2.6) are dissipative. This is of interest because as a matter of practical experience, dissipativity often ensures stability. For the case of a single interface it has been proved by Ciment [6] (for interfaces) and later by Goldberg and Tadmor [9] (for boundaries) that under reasonable hypotheses, this is always true. See also Sec. 6.2 of [24]. Later it was claimed by Olinger [17] that the same must hold with multiple interfaces. However the example above shows this is not so. We formulate this conclusion as a new proposition:

**PROPOSITION 4.** In a fixed- $\Delta_j$  model with two or more interfaces, such as an initial boundary value problem model with distinct boundary conditions at  $j = 0$  and  $j = 1$ , dissipativity of each individual difference formula is not sufficient to ensure stability.

It would of course be more satisfying to find an illustration of this principle that was somewhat realistic.

Example 2 also serves to illustrate another (weaker) stability principle. In some circles, where the Kreiss/Osher theory is considered too complicated for practical work, the "von Neumann" or "Fourier method" for heuristic stability analysis is used instead. This idea, proposed by Trapp and Ramshaw [23] (not by von Neumann), is to check the numerical boundary formulas for amplification factors greater than 1 just as if they were interior formulas, and hope that if there are none such, the model will be stable. In general there is little reason to expect this procedure to work, and indeed the heuristic justification of it by Trapp and Ramshaw is not really valid. Yet

because of the algebraic simplicity of the difference formulas usually encountered, the idea is surprisingly reliable in practice [22]. In particular, for a dissipative difference model with a solvable boundary condition applied at a single point, it can readily be shown that the Fourier condition is sufficient for stability [9].

But Example 4 confirms that the same does not hold when there is more than one boundary condition:

PROPOSITION 4'. In an initial boundary value problem model involving distinct boundary conditions at  $j = 0$  and  $j = 1$ , the "von Neumann method" of boundary condition analysis is not sufficient to ensure stability.

If the stability of each interface individually is not enough for a general stability test, what is? The unfortunate answer is that for a complete analysis one must investigate all possible modes  $z^n \phi_j$  suggested by Props. 1 or 2 to see if they satisfy the boundary conditions. The difficulty with the computation is that its size grows with the total width of the interface region: one must study a matrix function  $E(z)$  of dimension approximately  $\Delta j$  in the scalar case,  $N\Delta j$  in general. The required investigation can be prohibitively difficult.

However, various sufficient but not necessary conditions for stability can be derived that involve the interfaces individually. Consider the two-interface model  $\bar{Q} = Q_- | Q_0 | Q_+$  illustrated in Fig. 5. Here  $Q_-$ ,  $Q_0$ , and  $Q_+$  are constant-coefficient difference formulas with stencil parameters  $\{\ell_-, r_-\}$ ,  $\{\ell, r\}$ ,  $\{\ell_+, r_+\}$ , and  $j_1$  and  $j_2$  ( $> j_1$ ) are half-integers with  $\Delta j = j_2 - j_1 > 1$ . The interface at  $j_1$  consists simply of an abrupt change

from  $Q_-$  applied for  $j < j_1$  to  $Q_0$  applied for  $j > j_1$ , and similarly at  $j_2$ .

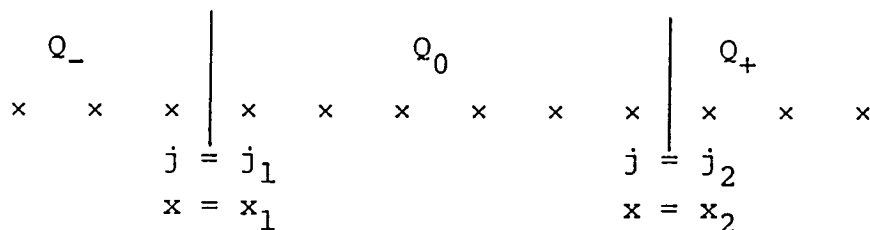


Figure 5. Two-interface model (fixed  $\Delta j$ )

We assume that each interface  $Q_-|Q_0$  and  $Q_0|Q_+$  is individually stable, and seek a condition to ensure that no unstable solution  $z^n \phi_j$  of  $\bar{Q}$  with  $|z| > 1$  (as in Fig. 4b) can exist. To ensure decoupling of  $Q_-$  and  $Q_+$ , we assume further  $r_- \leq r + \Delta j$  and  $l_+ \leq l + \Delta j$ .

Let  $Q_0$  admit  $R$  rightgoing and  $L$  leftgoing solutions, labeled as in (1.12). Let  $K(z)$  and  $M(z)$  be the  $R \times R$  and  $L \times L$  nonsingular matrices

$$K(z) = \text{diag}(\kappa_1, \dots, \kappa_R), \quad M(z) = \text{diag}(\mu_1, \dots, \mu_L),$$

and let  $V$  and  $W$  be the  $N \times R$  and  $N \times L$  matrices with columns  $V_m$  and  $W_m$ ,

$$V(z) = (V_1, \dots, V_R), \quad W(z) = (W_1, \dots, W_L).$$

Then (1.12) can be rewritten

$$v_j^n = z^n [V(z)K(z)^j \alpha + W(z)M(z)^j \beta]. \quad (2.7)$$

By definition of  $V$ ,  $K$ ,  $W$ , and  $M$ , this expression satisfies  $Q_0$  for all  $j$ , regardless of  $\alpha$  and  $\beta$ . Conversely, a function  $v_j^n = z^n \phi_j$  satisfies  $Q_0$  for  $j_1 < j < j_2$  only if it has a representation (2.7) valid in  $j_1 - \ell < j < j_2 + r$  for some  $\alpha$  and  $\beta$ . The question is, for which  $\alpha$  and  $\beta$ , if any, can a function  $v_j^n$  defined by (2.7) in  $j_1 - \ell < j < j_2 + r$  be extended to a solution of  $\bar{Q}$  for all  $j$  that is leftgoing in  $j < j_1$  and rightgoing in  $j > j_2$ ? The answer is: For precisely those  $\alpha, \beta$  satisfying the reflection equations

$$\alpha = A_1 \beta, \quad \beta = A_2 \alpha \quad (2.8)$$

where  $A_1$  is an  $R \times L$  matrix as in (2.3) relating  $\alpha$  to  $\beta$  at the  $Q_-|Q_0$  interface, and  $A_2$  is an  $L \times R$  matrix relating  $\beta$  to  $\alpha$  at  $Q_0|Q_+$ . This follows from the construction of (2.2). The assumption that each interface is stable in isolation has permitted us to pass from the form (2.2) to (2.3), since it implies by Prop. 1 that  $E_1(z)$  and  $E_2(z)$  are nonsingular for each  $|z| > 1$ .

The matrix  $A(z)$  of (1.15) was effectively defined with respect to the grid point  $j = 0$ , in the sense that it is at that point where a solution (1.12) to  $\bar{Q}$  has the form  $V\alpha + W\beta$  with  $\alpha = A(z)\beta$ . For the present problem, it is more natural for  $A_1$  to be defined with respect to the grid point  $j_1$ , and  $A_2$  with respect to  $j_2$ . We can accomplish this by replacing  $A_1$  in (2.8) by  $K^{-j_1} A_1 M^{j_1}$  and  $A_2$  by  $M^{-j_2} A_2 K^{j_2}$ . Equation (2.8) becomes

$$K(z)^{j_1} \alpha = A_1(z)M(z)^{j_1} \beta, \quad (2.9)$$

and

$$M(z)^{j_2} \beta = A_2(z)K(z)^{j_2} \alpha. \quad (2.10)$$

With this somewhat cumbersome notation it is possible to state a simple lemma on the existence of solutions  $v_j^n = z^n \phi_j$  to  $\bar{Q}$ .

**LEMMA 1.** The fixed- $\Delta j$  two-interface model  $\bar{Q}$  described above admits a solution  $v_j^n = z^n \phi_j$  with  $|z| > 1$  consisting of outgoing waves only in  $j < j_1$  and  $j > j_2$  if and only if the  $L \times L$  matrix

$$E_L(z) = M(z)^{-\Delta j} A_2(z)K(z)^{\Delta j} A_1(z) \quad (2.11)$$

has an eigenvalue 1.

Proof. Suppose  $\bar{Q}$  has a solution  $v_j^n = z^n \phi_j$  of the kind described. Let  $\alpha$  and  $\beta$  be the coefficient vectors for the representation (2.7) of  $v$  in  $j_1 - \ell < j < j_2 + r$ . By definition of  $A_1$  and  $A_2$ , the equations (2.9) and (2.10) must hold. Multiplying them together gives

$$M(z)^{j_2} \beta = A_2(z)K(z)^{\Delta j} A_1(z)M(z)^{j_1} \beta,$$

that is,

$$[M(z)^{j_1} \beta] = E_L(z)[M(z)^{j_1} \beta].$$

Thus  $M(z)^{j_1} \beta$  is an eigenvector of the sort required.



Conversely, if  $E_L(z)$  has an eigenvalue 1, let  $\beta$  be  $M(z)^{-j_1}$  times a corresponding eigenvector, and define  $\alpha$  by (2.9). Then by definition of  $\beta$ , (2.10) is satisfied also, so  $\bar{Q}$  has a solution of the required kind. ■

Lemma 1 now makes it possible to give sufficient conditions for stability based on  $A_1$  and  $A_2$  alone.

**PROPOSITION 5.** In the fixed- $\Delta j$  two-interface problem described above, in which each interface individually is stable, a sufficient condition for stability is

$$\|A_1(z)\| < 1, \quad \|A_2(z)\| < 1 \quad \text{for all } |z| > 1$$

in any norm  $\|\cdot\|$  subordinate to a vector norm, if at least one of the two inequalities is strict for each  $z$ .

Remark.  $A_1$  and  $A_2$  are rectangular matrices, i.e., operators  $A_1: \mathbb{C}^L \rightarrow \mathbb{C}^R$  and  $A_2: \mathbb{C}^R \rightarrow \mathbb{C}^L$ . The norms in Prop. 5 are the operator norms subordinate to any norms on  $\mathbb{C}^L$  and  $\mathbb{C}^R$ , which must however be the same for both  $A_1$  and  $A_2$ .

Proof. By the definitions of rightgoing and leftgoing we have  $|\kappa_m| < 1 < |\mu_m|$  for all  $z$  and  $m$ , hence  $\|K(z)\|, \|M(z)^{-1}\| < 1$  in any norm. Together with the hypotheses and (2.11) this implies  $\|E_L(z)\| < 1$  for each  $|z| > 1$ , which precludes the existence of the eigenvalue 1 of Lemma 1. ■

Example 3. Here we reproduce a "P-stability" result of Beam, Warming and Yee [1] by considering reflection coefficients. Let  $u_t = u_x$  on  $[0,1]$  be

modeled by any of the "A-stable" formulas  $Q$  of Beam and Warming, which consist of the usual three-point difference operator in  $x$  coupled with an A-stable linear multistep formula in  $t$ . Examples are the backward Euler and trapezoidal (= Crank-Nicolson) formulas. Let the boundary conditions be  $v^{n+1} = 0$  at  $x = 1$ ,  $j = \Delta j + 1 \geq 2$ , and  $q^{\text{th}}$ -order space extrapolation ( $q \leq \Delta j + 1$ )

$$(K-1)^q v_0^{n+1} = 0 \quad (2.12)$$

at  $x = j = 0$ , where  $K$  denotes the shift operator  $Kv_j^n = v_{j+1}^n$ . We claim that for any fixed  $\Delta j$ ,  $\bar{Q}$  admits no solution  $v_j^n = z^n \phi_j$  with  $|z| > 1$ .

Since the spatial difference in  $Q$  is just  $(K - K^{-1})$ , it is readily seen that for each  $|z| > 1$ ,  $Q$  admits one rightgoing wave  $z^n \kappa^j$  and one leftgoing wave  $z^n \mu^j$ , with  $\text{Re} \kappa < 0 < \text{Re} \mu$ ,  $|\kappa| < 1 < |\mu|$ , and  $\mu = -1/\kappa$ . The first inequality is derived as follows in Theorem 2.4.1 of [24]. If  $Q$  is A-stable, then  $\text{Re}(\kappa - 1/\kappa) < 0$  implies  $|z| < 1$ . Contrapositively,  $|z| > 1$  implies  $\text{Re}(\kappa - 1/\kappa) > 0$ . Since  $|\kappa| < 1$ , this means  $|z| > 1$  implies  $\text{Re} \kappa < 0$ .

Now we compute reflection coefficients. At  $j = \Delta j + 1/2$  one has

$$A_2 = -\sqrt{\kappa/\mu} = -i\kappa, \quad (2.13)$$

and at  $j = 1/2$ ,

$$A_1 = -\sqrt{\kappa/\mu} \left(\frac{\mu - 1}{\kappa - 1}\right)^q = -i\kappa^{1-q} \left(\frac{1 + \kappa}{1 - \kappa}\right)^q. \quad (2.14)$$

By the above inequalities one has  $|\frac{1 + \kappa}{1 - \kappa}| < 1$  for  $|z| > 1$ , and therefore

$$|A_2| < 1, \quad |A_1| < |\kappa|^{1-q}.$$

For  $q = 1$  both reflection coefficients have magnitude  $< 1$ , and by the argument of Prop. 5 we are done. If  $q > 1$ , the assumption  $\Delta j + 1 > q$  implies that the term  $K^{\Delta j}$  in (2.11) cancels any amplification due to the factor  $|\kappa|^{1-q}$  above, so stability follows from Lemma 1. Alternatively, to stick with the one-boundary-at-a-time approach of Prop. 5, one can renumber the vertices so that the lefthand boundary lies at  $j = q - 1/2$  instead of  $j = 1/2$ , and then  $|A_1|$  will be  $< 1$  regardless of  $q$ . //

Remark. A similar argument can be applied to the LF model (1.8) together with a space-time extrapolation condition such as  $v_0^{n+1} = v_1^n$ .

### 3. TWO INTERFACES SEPARATED BY A FIXED DISTANCE $\Delta x$

In this section we continue to investigate the configuration illustrated in Fig. 5, except that  $\Delta x$  rather than  $\Delta j$  will be held constant. Consider a two-interface model  $\bar{Q} = Q_- | Q_0 | Q_+$  in which the interfaces lie at positions  $x_1 = j_1 h$  and  $x_2 = j_2 h$ , and set  $\Delta x = x_2 - x_1$ . Either or both of the interfaces may in fact be a boundary; if both of them are, then  $\bar{Q}$  is a model for a differential equation on a strip such as  $[0,1]$ . We ask: as the mesh is refined, i.e., as  $h, k \rightarrow 0$  with  $x_1$  and  $x_2$  fixed, will the behavior of  $\bar{Q}$  be stable or unstable?

It is now that the distinction between stability and P-stability becomes important. Following Beam, Warming, and Yee [1], define:

Definition. The fixed- $\Delta x$  two-interface model  $\bar{Q}$  described above is P-stable if it is GKS-stable and in addition, for each fixed  $h > 0$  it admits no solutions  $v_j^n = z^n \phi_j$  with  $|z| > 1$  containing only leftgoing waves to the left and rightgoing waves to the right of both interfaces.

("P" stands for "practical".) Actually, P-stability is not a stability concept of the usual sort, since it is defined in terms of what eigensolutions  $\bar{Q}$  admits rather than what growth estimate it satisfies. But obviously this condition is vital if the time-dependent finite-difference model is to be used to approximate steady-state solutions, a procedure that is common in practice. In their tests Beam, et al. found P-stability of a linearized model problem to be a good indicator of success in practical nonlinear steady-state flow calculations [31].

We begin with the following result due to Kreiss:

PROPOSITION 6. The fixed- $\Delta x$  two-interface model described above is GKS-stable if and only if both interfaces  $Q_-|Q_0$  and  $Q_0|Q_+$  are individually GKS-stable.

Proof. See Section 11 of [10] and also Section 2 of [12]. The result refers specifically to GKS-stability, and is not necessarily valid for other definitions such as  $\lambda_2$ -stability. The basis of the argument is the invariance of GKS-stability with respect to perturbations of size  $O(k)$ ; the effect of each boundary on the other can be shown to be of this order as  $h, k \rightarrow 0$ . ■

The conclusion of Prop. 6 corresponds to what is often observed in practice: if each of two interfaces is GKS-stable, the computational results are usually satisfactory, while if one of them is not, they are usually wrong and sometimes explosively so. But this section can be viewed as an investigation of how Prop. 6 fails to tell the whole story. Our remaining results can be summarized as follows. Proposition 7 shows that repeated reflections between GKS-stable interfaces can cause P-unstable growth at a rate  $\text{const}^t$ , even though GKS-stability is maintained (cf. [1] and Section 7 of [10]). Proposition 8 shows that reflection between weakly GKS-unstable interfaces can cause catastrophic growth at the rate  $(\Delta j)^{\text{const } t}$  (cf. Section 17 of [14]). Proposition 9 shows that the latter problem will not occur when the unstable interfaces have finite reflection coefficients. Proposition 10 shows that dissipation prevents both growth phenomena (cf. [11]). Finally Prop. 11, like Prop. 5, shows that all growth can be ruled out if the reflection matrices at the two interfaces are known to satisfy  $\|A_i\| < 1$ .

**PROPOSITION 7.** GKS-stability does not imply P-stability. Specifically, let each interface in the fixed- $\Delta x$  two-interface model described above be GKS-stable. If the reflection matrix at one or both interfaces has norm greater than 1, then repeated reflections between the interfaces may lead to solution growth at the rate

$$\|v^n\| > (\text{const})^t \|v^0\|. \quad (3.1)$$

Proof. In the following discussion we first explain the growth rate  $\text{const}^t$  by two different heuristic arguments, which will be used again later in

this section. The purpose of these arguments is to show that, although growth at the rate (3.1) need not occur for every model satisfying the hypotheses, it is nevertheless the typical growth rate to be expected in such problems. The proof of the proposition as stated then consists of exhibiting Example 4. ■

Argument by repeated reflections. The principle of Prop. 7 is the same as that of Fig. 4, except that  $\Delta x$  rather than  $\Delta j$  is held constant. Suppose that for some  $|z| = 1$ , a (nondissipating) wave of frequency  $z$  exists which can travel leftwards with  $C < 0$ , reflect at the  $Q_-|Q_0$  interface into a rightgoing wave with  $C > 0$ , and then reflect at the  $Q_0|Q_+$  interface into the original leftgoing wave mode again. If the product of the two reflection coefficients in this circuit is greater than 1, then amplification has taken place, and it will be repeated in further reflections. The time taken to complete each circuit is roughly constant, independent of  $h$  and  $k$  as  $h, k \rightarrow 0$ . Therefore one must expect growth at the rate  $\text{const}^t$ .

Argument by perturbed reflection coefficients. If  $\bar{Q}$  permits geometric growth in  $t$ , we can expect the existence of an eigensolution  $v_j^n = z_0 \phi_j$  with  $|z_0| > 1$ ; the rate of growth will depend on how large  $|z_0|$  can be. For simplicity suppose that  $Q_0$  admits just one rightgoing mode  $z^n \kappa^j$  and one leftgoing mode  $z^n \mu^j$  for each  $|z| > 1$ , and as in the above argument, suppose that for some  $|z_0| = 1$  one has  $|\kappa| = |\mu| = 1$ ,  $C_\mu < 0 < C_\kappa$ , and  $|A_1 A_2| > 1$ . Then the diagonal matrices  $K$  and  $M$  of Section 2 reduce to  $\kappa$  and  $\mu$ , and the matrix  $E_L$  of (2.11) is a scalar with modulus  $|A_1 A_2|$ . Obviously this scalar is not equal to 1, so by Lemma 1,  $\bar{Q}$  does not have a solution  $z_0^n \phi_j$ . But suppose it happens that  $E_L = 1 + \text{const}$ , where, here and

from now on,  $\text{const}$  denotes a quantity of order of magnitude 1 that varies from one occurrence to the next and is positive except possibly for an imaginary part of size  $O(\varepsilon)$ , when this makes sense in context. To find a solution satisfying (2.7), consider  $z = z_0(1 + \varepsilon)$ ,  $0 < \varepsilon \ll 1$ . This perturbation changes  $\kappa$ ,  $\mu$ ,  $A_1$  and  $A_2$  by  $O(\varepsilon)$ . In particular  $\kappa$  and  $\mu$  become

$$\kappa \rightarrow \kappa(1 - \text{const}\varepsilon), \quad \mu \rightarrow \mu(1 + \text{const}\varepsilon).$$

(In the limit  $\varepsilon = 0$  the constants here are  $1/\lambda|C_\kappa|$  and  $1/\lambda|C_\mu|$ .) By (2.11)  $E_L$  therefore becomes

$$E_L = (1 + \text{const})(1 - \text{const}\varepsilon)^{\Delta j}.$$

For  $E_L$  to have value 1, the two factors have to balance, which means  $\varepsilon = O(1/\Delta j)$ . Therefore one can expect that any eigensolution  $z^n \phi_j$  to  $\bar{Q}$  will grow at the rate

$$\frac{\|v^n\|}{\|v^0\|} \approx |z|^n = \left(1 + \frac{\text{const}}{\Delta j}\right)^n = \left(1 + \frac{\text{const}}{\Delta j}\right)^{t\Delta j} = \text{const}^t,$$

as asserted in (3.1).

Example 4. Let  $u_t = u_x$  on  $[0,1]$  be approximated by the LF formula (1.8) together with the (admittedly contrived) boundary conditions

$$v_0^{n+1} = \frac{1}{2} (v_2^{n-1} + v_3^{n-2}), \quad v_{\Delta j+1}^{n+1} = 0. \quad (3.2)$$

The reflection coefficient functions are easily seen to be

$$A_1 = -\sqrt{\kappa/\mu} \frac{2z^3 - z\mu^2 - \mu^3}{2z^3 - z\kappa^2 - \kappa^3}, \quad A_2 = -\sqrt{\kappa/\mu}, \quad (3.3)$$

and since the denominators are never zero, both interfaces are GKS-stable. However,  $|A_1|$  can be larger than 1. For simplicity consider the semidiscrete limit  $\lambda = 0$ ,  $z = 1$ . By (1.17), for any  $\theta = \xi h \in [0, \pi/2)$ , LF then has a solution

$$z = 1, \quad \mu = e^{i\theta}, \quad \kappa = -e^{-i\theta}, \quad C_\mu = -\cos\theta, \quad C_\kappa = \cos\theta.$$

For any  $\theta$  with  $|A_1(\theta)| > 1$ , one can expect  $\bar{Q}$  to admit an eigensolution that grows approximately at the rate  $|A_1(\theta)|^{t \cos\theta/2}$ , since each circuit of a trapped wave packet will take time  $2/\cos\theta$ . The maximum of these rates for the given formulas turns out to be at  $\theta \approx .75$ , where one gets  $|A_1| \approx 2.38$ ,  $C \approx .725$ , and growth  $(1.37)^t$ . Numerical experiments confirm that solutions grow roughly at this rate, independent of  $h$  and  $k$ .

To establish Prop. 7 rigorously, one must prove that  $\bar{Q}$  admits the kind of growing eigensolution we have described. This can be done by using perturbation arguments based on the above heuristic reasoning to show that (2.11) in Lemma 1 has a solution with  $|z| \approx (1.37)^k$ . Since the conclusion is so obvious, we will not give details. //

The possibility of P-unstable growth as in Example 4 was recognized from the start by Gustafsson, Kreiss, and Sundström, and in fact Section 7 of [10] is devoted to determining when it will occur in a certain  $2 \times 2$  problem. In our particular example, the model remains P-unstable no matter how small  $h$  and



k become. Beam, et al. give the impression in various papers that this cannot happen, but that is true only when one is dealing with dissipative formulas; see Prop. 10 below. The reason that dissipation did not ensue P-stability for the values of h and k they were dealing with was that, because of their interest in steady-state results, they were using very large values of  $\lambda$ , and their formulas happened to be nondissipative in the limit  $\lambda \rightarrow \infty$ . Thus their computations made use of difference formulas that were dissipative but only weakly so.

Now let reflection coefficients be present that are not merely greater than 1, but infinite. The potential growth rate becomes much more severe.

**PROPOSITION 8.** Let one or both interfaces in the fixed- $\Delta x$  two-interface problem be algebraically GKS-unstable, with an infinite reflection coefficient. Then repeated reflections between the interfaces may sometimes lead to solution growth at the exponential rate

$$\|v^n\| > (\Delta j)^{\text{const } t} \|v^0\|. \quad (3.4)$$

Remark. For a single GKS-unstable interface with an infinite reflection coefficient, it is shown in [27] that the unstable growth is in general no worse than  $\|v^n\| \approx \text{const } n \|v^0\|$ . This is what is meant above by "algebraically" GKS-unstable.

Proof. Again we will motivate (3.4) by two arguments. Then we prove the proposition by exhibiting Example 5. ■

Argument by repeated reflections. Suppose  $A_1$  is infinite at  $z = z_0$ , and behaves near there like

$$\|A_1\| = \frac{\text{const}}{|z - z_0|}. \quad (3.5)$$

Since there are only  $\Delta j$  points between the interfaces for each fixed  $h$ , Fourier analysis implies that no wave on the  $Q_0$  grid can have a spectrum narrower than  $O(1/\Delta j)$ . Therefore it is plausible that in applying (3.5) to the finite grid, the largest amplification possible will be that obtained with an effective value  $z_{\text{eff}}$  with  $|z_{\text{eff}} - z_0| = \text{const}/\Delta j$ , i.e.,  $\|A_1\| \approx \text{const} \Delta j$ . Since as before each circuit takes roughly a fixed amount of time, independent of  $h$  and  $k$  as  $h, k \rightarrow 0$ , this leads immediately to (3.4).

Argument by perturbed reflection coefficients. As before, suppose that  $Q_0$  admits one leftgoing mode  $z^n \mu^j$  and one rightgoing mode  $z^n \kappa^j$  for each  $|z| > 1$ , and that for some  $|z_0| = 1$  one has  $|\kappa| = |\mu| = 1$ ,  $C_\mu < 0 < C_\kappa$ ,  $|A_1(z_0)| = \infty$ , and  $|A_2(z_0)| > 0$ . Suppose furthermore that  $A_1$  behaves like (3.5) for  $z \approx z_0$ . Then under the perturbation  $z = z_0(1 + \varepsilon)$  one has

$$\kappa \rightarrow \kappa(1 - \text{const}\varepsilon), \quad \mu \rightarrow \mu(1 + \text{const}\varepsilon), \quad E_L \rightarrow \frac{(1 - \text{const}\varepsilon)^{\Delta j}}{\varepsilon}.$$

For  $E_L = 1$  we must have  $(1 - \text{const}\varepsilon)^{\Delta j} = \varepsilon$ , which implies

$$\varepsilon \approx \frac{\text{const}}{\Delta j} \log(\Delta j).$$

Hence growth should be expected at the rate

$$\frac{\|v^n\|}{\|v^0\|} = |z|^n = \left(1 + \frac{\text{const} \log \Delta j}{\Delta j}\right)^{t \Delta j} = e^{t \text{const} \log \Delta j} = (\Delta j)^{\text{const} t}.$$

Example 5 ([14], Sec. 17). Let  $u_t = u_x$  on  $[0,1]$  be approximated by LF (1.8) with boundary conditions  $v_0^{n+1} = v_1^{n+1}$  (1.16) and  $v_{\Delta j+1}^{n+1} = 0$ . We have seen in (1.18) that this model has an infinite reflection coefficient at  $z = -1$ ; in fact one has as in Example 3

$$A_1(z) = -\sqrt{\kappa/\mu} \frac{1 - \mu}{1 - \kappa}, \quad A_2 = -\sqrt{\kappa/\mu}.$$

With these formulas (2.11) becomes

$$E_L(z) = (\kappa/\mu)^{\Delta j+1} \frac{1 - \mu}{1 - \kappa},$$

and since  $\mu = -1/\kappa$  for LF, this can be rewritten

$$E_L(z) = (-\kappa^2)^{\Delta j+1} \frac{1 + 1/\kappa}{1 - \kappa}.$$

Assume  $\Delta j+1$  is even, and write  $\kappa = 1 - \delta$ . The condition  $E_L(z) = 1$  becomes

$$(1 - \delta)^{2\Delta j+2} = \frac{\delta - \delta^2}{2 - \delta}.$$

It is obvious that this equation has a positive real solution near  $\delta = 0$ , which is asymptotic to  $\delta = \log \Delta j / 2\Delta j$  as  $\Delta j \rightarrow \infty$ . The corresponding value of  $z$  is asymptotic to

$$z = 1 + \frac{\lambda}{2} \frac{\log \Delta j}{\Delta j}.$$

Therefore  $\bar{Q}$  has an eigensolution which grows at the rate

$$\left(1 + \frac{\lambda}{2} \frac{\log \Delta_j}{\Delta_j}\right)^n = \left(1 + \frac{\lambda}{2} \frac{\log \Delta_j}{\Delta_j}\right)^{t\Delta_j/\lambda} \approx e^{t \log \Delta_j / 2} = (\Delta_j)^{t/2}.$$

This matches the result stated as (17.10) in [14], and numerical experiments confirm that physical solutions are rapidly obliterated by growth at the predicted rate. //

The possibility of catastrophic two-boundary interactions as in Prop. 8 has long been recognized by Kreiss and his colleagues, and it has been given sometimes as a justification of the apparent strictness of the GKS stability definition. We now show that this justification is only partial, for not all GKS-unstable boundaries have infinite reflection coefficients, yet an infinite reflection coefficient is required for the catastrophic two-boundary interaction to occur:

**PROPOSITION 9.** Let one or both interfaces in the fixed- $\Delta x$  two-interface problem be algebraically GKS-unstable, but with finite reflection coefficients only. Then  $\bar{Q}$  admits no eigensolutions  $v_j^n = z^n \phi_j$  that grow faster than  $(\text{const})^t$ .

Proof. Consider an eigensolution  $z^n \phi_j$  of  $\bar{Q}$ , and let  $M, K, A_2, A_1$  be the matrices of Lemma 1 for the given value  $z$ . By Lemma 1, the matrix

$$E_L = M^{-\Delta_j} A_2 K^{\Delta_j} A_1 \tag{3.6}$$

has an eigenvalue 1, which implies  $\|E_L\|_\infty > 1$ . On the other hand, the finite reflection coefficients assumption implies

$$\|A_1\|_\infty \|A_2\|_\infty < T \quad (3.7)$$

for some  $T < \infty$ . These bounds together yield

$$\|M^{-1}\|_\infty^{\Delta j} \|K\|_\infty^{\Delta j} > \frac{1}{T}$$

or in particular, since  $|\kappa| < 1 < |\mu|$  for each of the entries in  $M$  and  $K$ ,

$$|\kappa|, |\mu^{-1}| > \left(\frac{1}{T}\right)^{\frac{1}{\Delta j}} \quad (3.8)$$

for some  $\kappa$  and  $\mu$ .

Now the critical observation is that for any Cauchy stable formula  $Q$ ,  $|z|^{-1}$  is bounded by a multiple of  $1 - |\kappa|$  when the latter is small. For a proof, see Lemma 9.1 of [10]; the constant factor is essentially  $\lambda$  times the maximum group velocity admitted by  $Q$ . Therefore the last inequality implies

$$|z| < T^{\text{const}/\Delta j}$$

for large enough  $\Delta j$ . But this leads to

$$|z|^n < (T)^{\frac{n \text{ const}}{\Delta j}} = \text{const}^t,$$

which proves the theorem. ■

Now we come to the question of dissipation. In the fixed- $\Delta j$  situation, the use of dissipative formulas gave no guarantee of stability, because the

attenuation introduced by dissipation might always be overcome by amplification due to reflection at the boundaries. But in the fixed- $\Delta x$  problem, the attenuation of any nonphysical wave mode will increase as the mesh is refined. For fine enough meshes, this must overcome any finite amplification factors.

**PROPOSITION 10.** Let  $\bar{Q}$  be a GKS-stable, totally dissipative, consistent model of a fixed- $\Delta x$  two-interface problem. Let the solutions to the problem being modeled satisfy a bound

$$\|u(t)\| \leq \text{const } e^{-\text{const } t} \|u(0)\|.$$

Then for all sufficiently small  $h$  and  $k$ ,  $\bar{Q}$  is P-stable.

Remark. By "totally dissipative," we mean that the interior model  $Q$  dissipates oscillations with respect to  $t$  as well as  $x$ . For two-level formulas this is the same as the usual definition of dissipativity. For multilevel formulas, there is the additional requirement that the scheme admit no solutions  $v_j^n = z^n \phi$ ,  $\phi = \text{const}$ , with  $|z| = 1$  but  $z \neq 1$  [24].

Remark. This is an elaboration of the theorem stated by Gustafsson in [11]. See also [7].

Proof. We must show that  $\bar{Q}$  admits no eigensolution  $z^n \phi_j$  with  $|z| > 1$ , for large enough  $\Delta j$ . Suppose to the contrary that for a sequence of values  $\Delta j \rightarrow \infty$ ,  $\bar{Q}$  has a solution  $z^n \phi_j$  with  $|z| > 1$ . Since  $\bar{Q}$  is GKS-stable, it has finite reflection coefficients, so (3.6) - (3.8) of the last

proof are again valid. Equation (3.8) implies  $|\kappa| \uparrow 1$  and  $|\mu| \uparrow 1$  as  $\Delta j \rightarrow \infty$ . By dissipativity, this implies  $\kappa \rightarrow 1$  and  $\mu \rightarrow 1$ . By total dissipativity, this in turn implies  $z \rightarrow 1$  also. In other words, as  $\Delta j \rightarrow \infty$ , any eigensolutions of  $\bar{Q}$  have to approach physically meaningful solutions with low frequency and wave number.

Let the matrix  $A$  in the differential equation (1.1) have  $\tilde{L}$  positive and  $\tilde{R} = N - \tilde{L}$  negative eigenvalues. (There can be no zero eigenvalues, or the decay assumption would fail.) Consider the behavior of the  $L \times L$  matrix  $E_L$  of (3.6) as  $\Delta j \rightarrow \infty$  and  $z \rightarrow 1$ . By consistency,  $\tilde{L}$  values  $\mu$  and  $\tilde{R}$  values  $\kappa$  approach 1, while the remainder are bounded away from 1 in modulus. The powers  $M^{-\Delta j}$  and  $K^{\Delta j}$  in (3.6) therefore approach diagonal matrices containing  $\tilde{L}$  and  $\tilde{R}$  ones and  $L - \tilde{L}$  and  $R - \tilde{R}$  zeros, respectively. On the other hand, the reflection matrices  $A_1$  and  $A_2$  also approach limiting values, and by consistency, the restrictions of these to the  $\tilde{L} + \tilde{R}$  rows and columns corresponding to modes  $\kappa = 1$  or  $\mu = 1$  must equal the  $\tilde{R} \times \tilde{L}$  and  $\tilde{L} \times \tilde{R}$  reflection matrices  $\tilde{A}_1$  and  $\tilde{A}_2$  for the differential equation being modeled. Combining these observations, we obtain

$$E_L \rightarrow \tilde{E}_L \quad \text{as } \Delta j \rightarrow \infty,$$

where  $\tilde{E}_L$  is an  $L \times L$  matrix consisting of the  $\tilde{L} \times \tilde{L}$  matrix  $\tilde{A}_1 \tilde{A}_2$  padded with additional rows and columns of zeros.

Now by the decay assumption, the eigenvalues of  $\tilde{E}_L$  must be bounded below 1 in modulus; otherwise some eigenvector would describe a solution to the differential equation consisting of a wave that reflected back and forth without decaying. On the other hand by Lemma 1, we have assumed  $E_L$  has an eigenvalue 1. This is a contradiction. ■

Our final result is the same as Prop. 5, but restated for the fixed-  $\Delta x$  problem.

**PROPOSITION 11.** In the fixed- $\Delta x$  two-interface problem, in which each interface individually is GKS-stable, a sufficient condition for P-stability is

$$\|A_1(z)\| < 1, \quad \|A_2(z)\| < 1 \quad \text{for all } |z| > 1$$

in any norm subordinate to a vector norm, if at least one of the two inequalities is strict for each  $z$ .

Proof. Same as for Prop. 5. ■

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