




Centrum voor Wiskunde en Informatica

View metadata, citation and similar papers at core.ac.uk

brought to you by  CORE

provided by CWI's Institutions

REPORTRAPPORT

MAS

Modelling, Analysis and Simulation



Modelling, Analysis and Simulation

Bilinear forms for the recovery-based discontinuous Galerkin method for diffusion

M.H. van Raalte, B. van Leer

REPORT MAS-E0707 MAY 2007

Centrum voor Wiskunde en Informatica (CWI) is the national research institute for Mathematics and Computer Science. It is sponsored by the Netherlands Organisation for Scientific Research (NWO). CWI is a founding member of ERCIM, the European Research Consortium for Informatics and Mathematics.

CWI's research has a theme-oriented structure and is grouped into four clusters. Listed below are the names of the clusters and in parentheses their acronyms.

Probability, Networks and Algorithms (PNA)

Software Engineering (SEN)

Modelling, Analysis and Simulation (MAS)

Information Systems (INS)

Copyright © 2007, Stichting Centrum voor Wiskunde en Informatica
P.O. Box 94079, 1090 GB Amsterdam (NL)
Kruislaan 413, 1098 SJ Amsterdam (NL)
Telephone +31 20 592 9333
Telefax +31 20 592 4199

ISSN 1386-3703

Bilinear forms for the recovery-based discontinuous Galerkin method for diffusion

ABSTRACT

The present paper introduces bilinear forms that are equivalent to the recovery-based discontinuous Galerkin formulation introduced by Van Leer in 2005. The recovery method approximates the solution of the diffusion equation in a discontinuous function space, while inter-element coupling is achieved by a local L_2 projection that recovers a smooth continuous function underlying the discontinuous approximation. Here we introduce the concept of a local “recovery polynomial basis” - smooth polynomials that are in the weak sense indistinguishable from the discontinuous basis polynomials - and show it allows us to eliminate the recovery procedure. The recovery method reproduces the symmetric discontinuous Galerkin formulation with additional penalty-like terms depending on the targeted accuracy of the method. We present the unique link between the recovery method and discontinuous Galerkin bilinear forms.

2000 Mathematics Subject Classification: 65M60

Keywords and Phrases: discontinuous Galerkin method, higher-order discretization

Bilinear forms for the recovery-based discontinuous Galerkin method for diffusion

Marc van Raalte* and Bram van Leer†

Abstract

The present paper introduces bilinear forms that are equivalent to the recovery-based discontinuous Galerkin formulation introduced by Van Leer in 2005. The recovery method approximates the solution of the diffusion equation in a discontinuous function space, while inter-element coupling is achieved by a local L_2 projection that recovers a smooth continuous function underlying the discontinuous approximation. Here we introduce the concept of a local “recovery polynomial basis” - smooth polynomials that are in the weak sense indistinguishable from the discontinuous basis polynomials - and show it allows us to eliminate the recovery procedure.

The recovery method reproduces the symmetric discontinuous Galerkin formulation with additional penalty-like terms depending on the targeted accuracy of the method. We present the unique link between the recovery method and discontinuous Galerkin bilinear forms.

Key words: discontinuous Galerkin method, higher-order discretization

1 Introduction

Highly accurate schemes for solving the advection equation are preferably obtained by means of the discontinuous Galerkin (DG) method. This method approximates the solution in an element-wise continuous function space that is globally discontinuous. Because of the physics of advection, the method acquires a natural upwind character that renders the discontinuities at the cell interfaces harmless and stabilizes the scheme.

When combining advection with diffusion, though, we run into a problem: the discontinuous function space that works so well for advection does not

*NWO 635.100.009

†AFOSR FA9950-06-1-0425

combine naturally with the diffusion operator. In the course of 25 years, various bilinear DG forms have been introduced for approximation of the diffusion operator; the symmetric DG form, stabilised either with the penalty term of Arnold[1] or the penalty term of Brezzi [2], are most widely used.

In constructing bilinear forms for diffusion, the essence lies in choosing the numerical fluxes that are responsible for the coupling of the discontinuous solution approximation across the cell interfaces. Traditionally, these numerical fluxes are defined such that the bilinear form satisfies a number of mathematical conditions (the more the better) such as symmetry, coercivity and boundedness. Until recently, however, an analysis in which bilinear forms for diffusion, with desirable mathematical properties, appear simply as a result of a physical argument, was lacking.

In 2005 Van Leer et. al. presented the “recovery method.” Here the coupling through the numerical fluxes is obtained by arguing that, for diffusion, the discontinuous solution approximation should locally be regarded as an L_2 projection of a higher-order continuous function. This local “recovered” function couples neighboring cells and provides the information for computing the diffusive fluxes.

In the present paper we consider the 1-D diffusion equation in order to present the link between the recovery method and traditional discontinuous Galerkin bilinear formulations. Key to the systematic derivation of the diffusive fluxes that appear in the bilinear forms is the discovery of the “recovery polynomial basis:” to each piecewise continuous polynomial basis of degree k defined on two adjacent cells corresponds a *unique* continuous polynomial space of degree $2k + 1$. In consequence, to the approximation of the solution as an expansion in the discontinuous basis functions locally corresponds an *identical* expansion in the smooth recovery basis; the latter permits computing of the numerical fluxes across the cell interfaces. And, because of the duality of the polynomial spaces, the numerical fluxes in terms of the discontinuous basis functions follow immediately.

Thus, for any polynomial space of degree k the recovery method is equivalent to a unique, basis-independent bilinear discontinuous Galerkin formulation.

The outline of the paper is as follows. In the next section the recovery method is reviewed, in Section 3 the recovery basis is introduced, and in Section 4 the numerical fluxes are computed. These lead to the bilinear forms presented in Section 5. The final section lists the paper’s conclusions.

2 The recovery method

Let us consider the diffusion equation $u_t = Du_{xx}$ which for convenience we discretize on the regular infinite grid

$$\mathbb{Z}_h = \{jh \mid j \in \mathbb{Z}, h > 0\}. \quad (1)$$

On the partitioning of open cells $\Omega_j =]jh, (j+1)h[$ we introduce the function space associated with discontinuous Galerkin methods

$$\mathcal{P}^k(\mathbb{Z}_h) = \{w : w \in \mathcal{P}^k(\Omega_j), j \in \mathbb{Z}\}, \quad (2)$$

with $\mathcal{P}^k(\Omega_j)$ a polynomial space of degree k , and we introduce the jump and average operators that are useful for discontinuous Galerkin formulations. For a function w we define

$$\begin{aligned} [w]|_{(j+1)h} &= w|_{\Omega_j} \mathbf{n}_{\Omega_j} + w|_{\Omega_{j+1}} \mathbf{n}_{\Omega_{j+1}}, \\ \langle w \rangle|_{(j+1)h} &= \frac{1}{2} \left(w|_{\Omega_j} + w|_{\Omega_{j+1}} \right). \end{aligned} \quad (3)$$

Here, \mathbf{n}_{Ω_j} is the one-dimensional outward normal of cell Ω_j at point $(j+1)h$.

The recovery method for the 1-D diffusion equation is based on the following weak formulation: find $u \in \mathcal{P}^k(\mathbb{Z}_h)$ such that

$$\begin{aligned} \sum_{\Omega_j \in \mathbb{Z}} \int_{\Omega_j} u_t v dx &= D \sum_{\Omega_j \in \mathbb{Z}} \int_{\Omega_j} u v_{xx} dx + \\ &D \left([v] f_x|_{\Gamma_{\text{int}}} - [v_x] f|_{\Gamma_{\text{int}}} \right), \quad \forall v \in \mathcal{P}^k(\mathbb{Z}_h), \end{aligned} \quad (4)$$

where $\Gamma_{\text{int}} = \{jh\}_{j \in \mathbb{Z}}$ is the set of cell-interfaces and f is the locally recovered smooth function whose value and derivative we use at each cell interface $x = eh$, $e \in \mathbb{Z}$. The recovery requirement is that f is indistinguishable from u in the weak sense on the cells Ω_{e-1} and Ω_e , meaning that we find $f \in \mathcal{P}^{2k+1}(\Omega_{e-1} \cup \Omega_e)$ such that

$$\sum_{j=e-1,e} \int_{\Omega_j} f v dx = \sum_{j=e-1,e} \int_{\Omega_j} u v dx, \quad \forall v \in \mathcal{P}^k(\Omega_{e-1}) \cup \mathcal{P}^k(\Omega_e). \quad (5)$$

In Van Leer et al. [3, 4] we have presented linear systems from which the polynomial coefficients of f follow. In the next section we introduce a new concept, the recovery basis, which is at the heart of the recovery procedure; it greatly simplifies both computation and further analysis of the diffusive fluxes.

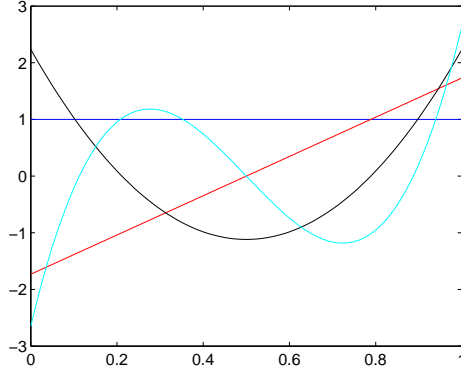


Figure 1: The first four orthonormal Legendre polynomials $\phi_0(\xi) = 1$, $\phi_1(\xi) = \sqrt{3}(-1 + 2\xi)$, $\phi_2(\xi) = \sqrt{5}(1 - 6\xi + 6\xi^2)$ and $\phi_3(\xi) = \sqrt{7}(-1 + 12\xi - 30\xi^2 + 20\xi^3)$ defined on the interval $\xi \in]0, 1[$.

3 The recovery basis

As the basis for (2) we consider polynomials $\phi_i(\xi)$ in the hierarchical space $\mathcal{P}^k(]0, 1[)$ of degree k that satisfy

$$\int_0^1 \phi_i(\xi)\phi_l(\xi)d\xi = \begin{cases} 0 & \text{if } i \neq l \\ 1 & \text{if } i = l \end{cases} \quad \text{with } i \text{ and } l = 0, \dots, k. \quad (6)$$

For the sake of determinacy (it is not essential), we choose the orthonormal Legendre polynomials defined on the open interval $\xi \in]0, 1[$ (see [5], page 775):

$$\phi_n(\xi) = \frac{1}{2^n} \sqrt{2n+1} \sum_{m=0}^{\lfloor n/2 \rfloor} (-1)^m \binom{n}{m} \binom{2n-2m}{n} (-1+2\xi)^{n-2m}. \quad (7)$$

Figure 1 shows the first four polynomials of this basis. On the grid (1), the function space (2) is spanned by the piecewise continuous polynomials

$$\phi_{i,j}(x) = \begin{cases} \phi_i\left(\frac{x-jh}{h}\right) & x \in \Omega_j, \\ 0 & \text{otherwise.} \end{cases} \quad (8)$$

To obtain a L_2 approximation of a given smooth function $U(x)$ (for instance an initial-value distribution) we solve the bilinear form: find $u \in \mathcal{P}^k(\mathbb{Z}_h)$ such that

$$\sum_{j \in \mathbb{Z}} \int_{\Omega_j} u \phi_{i,j} dx = \sum_{j \in \mathbb{Z}} \int_{\Omega_j} U \phi_{i,j} dx, \quad \forall \phi_{i,j} \in \mathcal{P}^k(\mathbb{Z}_h). \quad (9)$$

With the approximation

$$u = \sum_{j \in \mathbb{Z}} \sum_{i=0}^k c_{i,j} \phi_{i,j}(x), \quad (10)$$

and using (6), the solution of (9) reads

$$c_{i,j} = \int_0^1 U(h(\xi + j)) \phi_i(\xi) d\xi, \quad i = 0, \dots, k, \quad j \in \mathbb{Z}. \quad (11)$$

The L_2 approximation (10) is in general *discontinuous* at the cell-interfaces. The function values and derivatives of $u(x)$ are formally not defined at the nodal points jh , whereas they were for $U(x)$. This motivates recovery.

We shall now go to the root of the recovery procedure. We consider two adjacent cells Ω_e and Ω_{e+1} and describe the local recovery procedure (5) for the piecewise continuous approximation (10). On the union of the cells we introduce the basis polynomials (to be specified later)

$$\psi_{i,j}(x) = \begin{cases} \psi_i\left(\frac{x-jh}{h}\right) & x \in \Omega_j \cup \Omega_{j+1}, \quad i = 0, \dots, 2k+1, \\ 0 & \text{otherwise.} \end{cases} \quad (12)$$

with $\psi_i(\xi) \in \mathcal{P}^{2k+1}([0, 2])$, and we construct the polynomial space

$$\mathcal{P}^{2k+1}(\Omega_e \cup \Omega_{e+1}) = \text{Span} \{ \psi_{i,j}(x) \}, \quad j = e, \quad i = 0, \dots, 2k+1. \quad (13)$$

Writing the recovered smooth approximation as

$$f = \sum_{i=0}^{2k+1} a_i \psi_{i,e}(x), \quad x \in \Omega_e \cup \Omega_{e+1}, \quad (14)$$

our task is solving the bilinear form: find $f \in \mathcal{P}^{2k+1}(\Omega_e \cup \Omega_{e+1})$ such that

$$\sum_{j \in \mathbb{Z}} \int_{\Omega_j} f \phi_{i,j} dx = \sum_{j \in \mathbb{Z}} \int_{\Omega_j} u \phi_{i,j} dx = h c_{i,j}, \quad j = e, e+1, \quad i = 0, \dots, k. \quad (15)$$

This implies solving the linear system

$$\begin{bmatrix} \int_0^1 \psi_0(\xi) \phi_0(\xi) d\xi & \cdots & \int_0^1 \psi_{2k+1}(\xi) \phi_0(\xi) d\xi \\ \vdots & \cdots & \vdots \\ \int_0^1 \psi_0(\xi) \phi_k(\xi) d\xi & \cdots & \int_0^1 \psi_{2k+1}(\xi) \phi_k(\xi) d\xi \\ \int_0^1 \psi_0(\xi+1) \phi_0(\xi) d\xi & \cdots & \int_0^1 \psi_{2k+1}(\xi+1) \phi_0(\xi) d\xi \\ \vdots & \cdots & \vdots \\ \int_0^1 \psi_0(\xi+1) \phi_k(\xi) d\xi & \cdots & \int_0^1 \psi_{2k+1}(\xi+1) \phi_k(\xi) d\xi \end{bmatrix} \begin{bmatrix} a_0 \\ \vdots \\ a_k \\ a_{k+1} \\ \vdots \\ a_{2k+1} \end{bmatrix} = \begin{bmatrix} c_{0,e} \\ \vdots \\ c_{k,e} \\ c_{0,e+1} \\ \vdots \\ c_{k,e+1} \end{bmatrix} \quad (16)$$

We now make the key observation: if we choose the $\psi_{i,e}(x)$ such that the matrix in (16) renders an *identity* matrix, the expansion of f in terms of the smooth basis is *identical* to the expansion of u in terms of the discontinuous basis. Then we will have $a_i = c_{i,e}$ and $a_{k+1+i} = c_{i,e+1}$ for $i = 0, \dots, k$, and

$$\begin{aligned} u|_{\Omega_e \cup \Omega_{e+1}} &= \sum_{i=0}^k c_{i,e} \phi_{i,e}(x) + \sum_{i=0}^k c_{i,e+1} \phi_{i,e+1}(x), \\ f &= \sum_{i=0}^k c_{i,e} \psi_{i,e}(x) + \sum_{i=0}^k c_{i,e+1} \psi_{k+1+i,e}(x), \quad x \in \Omega_e \cup \Omega_{e+1}. \end{aligned} \quad (17)$$

To achieve this simplicity we must require

$$\begin{aligned} \left[\begin{aligned} \int_0^1 \psi_i(\xi) \phi_l(\xi) d\xi &= \begin{cases} 1 & i = l \\ 0 & i \neq l \end{cases} \\ \int_0^1 \psi_i(\xi + 1) \phi_l(\xi) d\xi &= 0 \end{aligned} \right. \\ &\quad \text{for } i \text{ and } l = 0, \dots, k. \quad (18) \\ \left[\begin{aligned} \int_0^1 \psi_{k+1+i}(\xi) \phi_l(\xi) d\xi &= 0 \\ \int_0^1 \psi_{k+1+i}(\xi + 1) \phi_l(\xi) d\xi &= \begin{cases} 1 & i = l \\ 0 & i \neq l \end{cases} \end{aligned} \right. \end{aligned}$$

This set of equations represents a weak interpolation problem and, just as for strong collocation interpolation, has a unique solution for each basis $\{\phi_i\}$. In consequence, each basis in the discontinuous polynomial space $\mathcal{P}^k(\Omega_e) \cup \mathcal{P}^k(\Omega_{e+1})$ has a unique recovery counterpart in $\mathcal{P}^{2k+1}(\Omega_e \cup \Omega_{e+1})$.

The discontinuous and smooth recovery polynomial bases satisfying (18) are given in Table 1 for some values of k . Figure 2 shows the the discontinuous orthonormal Legendre polynomials and the corresponding smooth recovery polynomials for $k = 1$. Figure 3 shows the piecewise constant function and its recovery counterpart for $k = 0$ to 3. The smooth basis function tends weakly to the underlying discontinuous one as k is increased. Figure 4 shows the L_2 approximation according to (17) of $f = \cos(\frac{9\pi}{4h}x)$ both in the discontinuous basis (left) and in the recovery basis (right) . In the latter representation we can compute unique values of the function and its derivative at the cell interface.

4 Numerical fluxes

We are now ready to express the diffusive fluxes in (4), recovered according to (5), in terms of the discontinuous polynomials in the function space (2) for any degree k ; we shall restrict ourselves to lower values of k .

Table 1: The orthonormal Legendre basis and the recovery basis for degrees $k = 0, 1$ and 2 . The recovery basis satisfies the orthonormality conditions (18) and makes the matrix in (16) the identity matrix.

k	$\phi_i(\xi)$ $0 < \xi < 1, \quad i = 0, \dots, k$	$\psi_i(\xi)$ $0 < \xi < 2, \quad i = 0, \dots, 2k + 1$
0	1	$\frac{3}{2} - \xi$ $-\frac{1}{2} + \xi$
1	1 $(-1 + 2\xi)\sqrt{3}$	$\frac{1}{4} + \frac{21}{4}\xi - \frac{15}{2}\xi^2 + \frac{5}{2}\xi^3$ $(-\frac{23}{12} + \frac{33}{4}\xi - \frac{17}{2}\xi^2 + \frac{5}{2}\xi^3)\sqrt{3}$ $(-\frac{7}{12} + \frac{17}{4}\xi - \frac{13}{2}\xi^2 + \frac{5}{2}\xi^3)\sqrt{3}$
2	1 $(-1 + 2\xi)\sqrt{3}$ $(1 - 6\xi + 6\xi^2)\sqrt{5}$	$\frac{9}{4} - \frac{75}{4}\xi + \frac{135}{2}\xi^2 - \frac{185}{2}\xi^3 + \frac{105}{2}\xi^4 - \frac{21}{2}\xi^5$ $(\frac{3}{8} - \frac{147}{8}\xi + \frac{1155}{16}\xi^2 - \frac{775}{8}\xi^3 + \frac{1715}{32}\xi^4 - \frac{21}{2}\xi^5)\sqrt{3}$ $(\frac{99}{40} - \frac{1083}{40}\xi + \frac{1233}{16}\xi^2 - \frac{713}{8}\xi^3 + \frac{1449}{32}\xi^4 - \frac{42}{5}\xi^5)\sqrt{5}$ $-\frac{5}{4} + \frac{75}{4}\xi - \frac{135}{2}\xi^2 + \frac{185}{2}\xi^3 - \frac{105}{2}\xi^4 + \frac{21}{2}\xi^5$ $(\frac{9}{8} - \frac{137}{8}\xi + \frac{1005}{16}\xi^2 - \frac{705}{8}\xi^3 + \frac{1645}{32}\xi^4 - \frac{21}{2}\xi^5)\sqrt{3}$ $(-\frac{29}{40} + \frac{453}{40}\xi - \frac{687}{16}\xi^2 + \frac{503}{8}\xi^3 - \frac{1239}{32}\xi^4 + \frac{42}{5}\xi^5)\sqrt{5}$

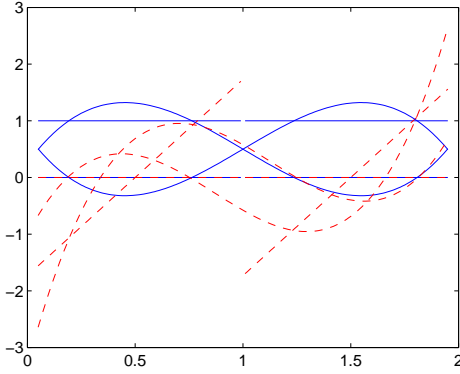


Figure 2: The discontinuous and recovery basis for $k = 1$ and cells Ω_0 and Ω_1 with $h = 1$.

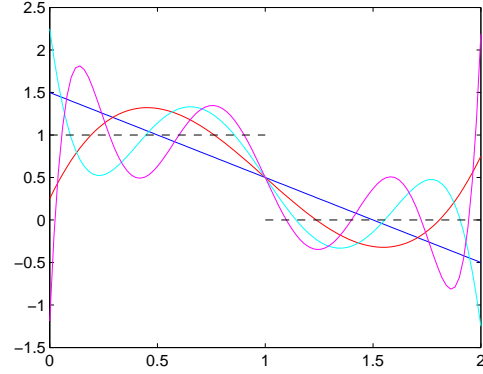


Figure 3: The piecewise constant function and its counterpart in the recovery basis for $k = 0$ to 3 .

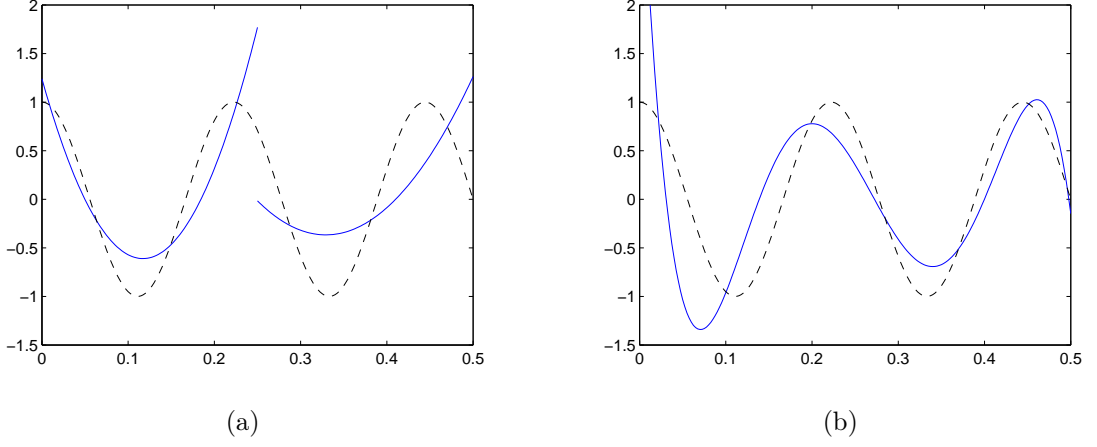


Figure 4: L_2 approximation of $f = \cos(\frac{9\pi}{4h}x)$ on cells Ω_0 and Ω_1 ($h=1/4$). (a) the approximation in the Legendre basis with $k = 2$, (b) the corresponding recovered function in the recovery basis.

We first consider the case $k = 1$. Using the expansion (17) of f and the relevant entries for ψ_i from table 1 we compute the trace at $x = (e + 1)h$:

$$\begin{aligned} f((e + 1)h) &= \sum_{i=0,1} c_{i,e} \psi_i(1) + \sum_{i=0,1} c_{i,e+1} \psi_{2+i}(1), \\ &= \frac{1}{2}c_{0,e} + \frac{1}{3}c_{1,e}\sqrt{3} + \frac{1}{2}c_{0,e+1} - \frac{1}{3}c_{1,e+1}\sqrt{3}. \end{aligned} \quad (19)$$

Comparing this result with the expansion of u we see, with $\varepsilon \rightarrow 0$, that

$$\begin{aligned} u((j + 1)h - \varepsilon) &= \sum_{i=0,1} c_{i,e} \phi_i(1) = c_{0,e} + c_{1,e}\sqrt{3}, \\ u((j + 1)h + \varepsilon) &= \sum_{i=0,1} c_{i,e+1} \phi_i(0) = c_{0,e+1} - c_{1,e+1}\sqrt{3}. \end{aligned} \quad (20)$$

Applying the jump and average operators and using the fact that the Legendre basis is hierarchical we find

$$f((e + 1)h) = \langle u \rangle|_{(e+1)h} - \frac{1}{12}h [u_x]|_{(e+1)h}, \quad (21)$$

and analogously

$$f_x((e + 1)h) = -\frac{9}{4h} [u]|_{(e+1)h} + \langle u_x \rangle|_{(e+1)h}. \quad (22)$$

Table 2: The expansion of (21) and (22) for discontinuous polynomial space of degree $k = 0, 1$ and 2 .

k	$f(jh)$	$f_x(jh)$
0	$\langle u \rangle$	$-\frac{1}{h} [u]$
1	$\langle u \rangle - \frac{1}{12} h [u_x]$	$-\frac{9}{4h} [u] + \langle u_x \rangle$
2	$\langle u \rangle - \frac{3}{64} h [u_x]$	$-\frac{15}{4h} [u] + \langle u_x \rangle - \frac{9}{240} h [u_{xx}]$

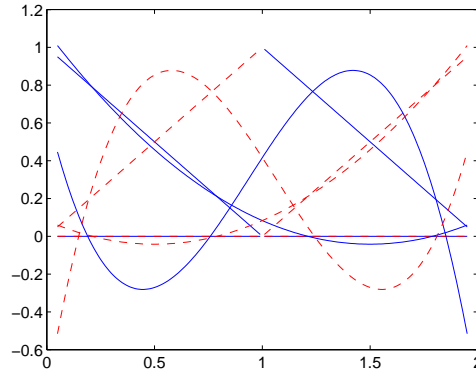


Figure 5: The typical finite-element hat-polynomials and their recovery counterpart. In these bases, the expansions (17) hold.

The derivation for other polynomial degrees is similar to the above procedure; Table 2 shows the results for $k = 0$ to 2 . As indicated before, and verifiable by construction, for a given degree k , to each Legendre polynomial (7) in the function space $\mathcal{P}^k(\Omega_e) \cup \mathcal{P}^k(\Omega_{e+1}) \subset \mathcal{P}^k(\mathbb{Z}_h)$ corresponds a *unique* recovery polynomial in the function space $\mathcal{P}^{2k+1}(\Omega_e \cup \Omega_{e+1})$. In consequence, basis transformations apply on both polynomial spaces simultaneously, with the result that any polynomial in the space $\mathcal{P}^k(\Omega_e) \cup \mathcal{P}^k(\Omega_{e+1}) \subset \mathcal{P}^k(\mathbb{Z}_h)$ has a unique recovery polynomial in the space $\mathcal{P}^{2k+1}(\Omega_e \cup \Omega_{e+1})$. As an example we show in Figure 5 the typical finite-element hat-polynomials and their recovery counterparts satisfying the expansions (17). Two of the four hat polynomials are continuous at $x = 1$, with the result that the corresponding recovery polynomial becomes a good approximation.

Because of the existence of the recovery polynomials, which span $\mathcal{P}^{2k+1}(\Omega_e \cup \Omega_{e+1})$, the recovered approximation $f \in \mathcal{P}^{2k+1}(\Omega_e \cup \Omega_{e+1})$ is independent of the basis on which it was computed and, likewise, the resulting diffusive fluxes are basis independent. Hence, starting from the hat-polynomials ($k=1$), one

finds the same interface values of f and f_x as given in (21) and (22).

5 Bilinear forms for the recovery method

Given the unique expansions for several k in Table 2 we may finely reformulate the recovery method (4) with its recovery procedure (5) for these degrees as: find $u \in \mathcal{P}^k(\mathbb{Z}_h)$ such that

$$B_k(u, v) = \frac{1}{D} \sum_{\Omega_j \in \mathbb{Z}_h} \int_{\Omega_j} u_t v dx, \quad \forall v \in \mathcal{P}^k(\mathbb{Z}_h), \quad (23)$$

where ¹

$$k = 0: B_0(u, v) = -\frac{1}{h} [v] [u]_{\Gamma_{\text{int}}}, \quad (24)$$

$$k = 1: B_1(u, v) = - \sum_{\Omega_j \in \mathbb{Z}_h} \int_{\Omega_j} u_x v_x dx + [v] \langle u_x \rangle_{\Gamma_{\text{int}}} + \quad (25)$$

$$\langle v_x \rangle [u]_{\Gamma_{\text{int}}} - \frac{9}{4h} [v] [u]_{\Gamma_{\text{int}}} + \frac{1}{12} h [v_x] [u_x]_{\Gamma_{\text{int}}},$$

$$k = 2: B_2(u, v) = - \sum_{\Omega_j \in \mathbb{Z}_h} \int_{\Omega_j} u_x v_x dx + [v] \langle u_x \rangle_{\Gamma_{\text{int}}} + \quad (26)$$

$$\langle v_x \rangle [u]_{\Gamma_{\text{int}}} - \frac{15}{4h} [v] [u]_{\Gamma_{\text{int}}} + \frac{3}{64} h [v_x] [u_x]_{\Gamma_{\text{int}}} - \frac{9}{240} h [v] [u_{xx}]_{\Gamma_{\text{int}}}.$$

Clearly, the recovery-based discontinuous Galerkin method for $k \geq 1$ reproduces the symmetric weak formulation, with a sequence of penalty-like terms; The number of terms and their coefficients depend on the targeted accuracy of the method. For any k Arnold's [1] interior penalty term appears. Note that for $k = 2$ the last term is not symmetric. Higher-degree bilinear forms are obtainable by straightforward construction.

6 Conclusion

In this article we have derived bilinear forms for the recovery-based discontinuous Galerkin method for the discretization of the 1-D diffusion equation.

¹Here we use that

$$\sum_{\Omega_j \in \mathbb{Z}_h} \int_{\Omega_j} u v_{xx} dx = - \sum_{\Omega_j \in \mathbb{Z}_h} \int_{\Omega_j} u_x v_x dx + [u v_x]_{\Gamma_{\text{int}}}$$

and $[v_x] \langle u \rangle = - \langle v_x \rangle [u]_{\Gamma_{\text{int}}} + [u v_x]_{\Gamma_{\text{int}}}$.

This method approximates the solution of the diffusion equation in a discontinuous function space, while inter-element coupling is achieved by locally recovering a higher-order continuous function from the continuous function.

At the heart of this recovery procedure is the existence of the recovery basis polynomials: polynomials, defined on two cells, that are in L_2 -sense indistinguishable from the discontinuous basis functions.

An important property is that for a fixed degree to each non-smooth basis function in the discontinuous function space corresponds a unique locally smooth polynomial in the recovery function space, and visa-versa. We have shown that the diffusive flux (function value or derivative) computed from the recovered smooth approximation, expressed in terms of the interface jumps and averages of the discontinuous approximation, is unique; in particular it is independent of the bases in which the discontinuous and smooth approximations were expressed.

The recovery method reproduces the symmetric discontinuous Galerkin formulation, augmented with a number of not necessarily symmetric penalty terms; the number increases with the degree of the approximation space.

We submit this paper provides the tools to further analyse the stability and accuracy of the recovery-based discontinuous Galerkin method.

References

- [1] D.N. Arnold, An interior penalty finite element method with discontinuous elements, *SIAM J.Numer.Anal.*,19:742-760, 1982.
- [2] F. Brezzi, M. Manzini, D. Marini, P. Pietra, A. Russo, Discontinuous Galerkin approximations for elliptic problems, *Numer. Methods Partial Differential Eq.*, 16: 365-278, 2000.
- [3] Bram van Leer and Shohei Nomura, Discontinuous Galerkin for Diffusion, *AIAA paper*, 2005-5108, 2005.
- [4] Bram van Leer, Marcus Lo and Marc van Raalte. A Discontinuous Galerkin Method for Diffusion Based on Recovery. *To be presented at the 18th AIAA Computational Fluid Dynamics Conference 25-28 June 2007, Miami, FL.*
- [5] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions*, National Bureau of Standards,Dover, New York, 1999.