Cover Sheet – Applied Analysis Part

**Policy on misprints:** The qualifying exam committee tries to proofread exams as carefully as possible. Nevertheless, the exam may contain a few misprints. If you are convinced a problem has been stated incorrectly, indicate your interpretation in writing your answer. In such cases, do *not* interpret the problem so that it becomes trivial.

Name

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**Combined Applied Analysis/Numerical Analysis Qualifier**

**Applied Analysis Part**

**January 14, 2015**

**Instructions:** Do any 3 of the 4 problems in this part of the exam. Show all of your work clearly. Please indicate which of the 4 problems you are skipping.

**Problem 1.** State and prove the Shannon sampling theorem.

**Problem 2.** Let $\mathcal{D}$ be the set of compactly supported functions defined on $\mathbb{R}$ and let $\mathcal{D}'$ be the corresponding set of distributions.

(a) Define convergence in $\mathcal{D}$ and $\mathcal{D}'$.
(b) Give an example of a function in $\mathcal{D}$.
(c) Show that $\psi \in \mathcal{D}$ has the form $\psi(x) = (x\phi(x))'$ for some $\phi \in \mathcal{D}$ if and only if $\int_{-\infty}^{\infty} \psi(x)dx = \int_{0}^{\infty} \psi(x)dx = 0$.
(d) Use 2(c) to show that if $T \in \mathcal{D}'$ satisfies $xT'(x) = 0$, then $T(x) = c_1 1 + c_2 H(x)$, where $H$ is the Heaviside step function.

**Problem 3.** Let $\mathcal{H}$ be a (separable) Hilbert space and let $\mathcal{B}(\mathcal{H})$ be the Banach space of bounded operators on $\mathcal{H}$. In addition, let $\mathcal{C}(\mathcal{H})$ be the subspace of $\mathcal{B}(\mathcal{H})$ comprising the compact operators on $\mathcal{H}$.

(a) Show that $\mathcal{C}(\mathcal{H})$ is closed in $\mathcal{B}(\mathcal{H})$.
(b) Define the term *Hilbert-Schmidt operator*. Show that if $K$ is Hilbert-Schmidt, then it is compact. (You may assume that $K \in \mathcal{B}(\mathcal{H})$.)
(c) Find the Green’s function $G(x,y)$ for boundary value problem

$$ u'' = f, \hspace{1em} u(0) = 0, \hspace{1em} u(1) = 0, $$

and show that $Gf(x) = \int_{0}^{1} G(x,y) f(y) dy$ is compact.

**Problem 4.** Let $\mathcal{P}$ be the set of all polynomials in $x$.

(a) State and sketch a proof of the Weierstrass approximation theorem.
(b) Show that $\mathcal{P}$ is dense in $L^2[0,1]$.
(c) Let $\mathcal{U} := \{p_n\}_{n=0}^{\infty}$ be the orthonormal set of polynomials obtained from $\mathcal{P}$ via the Gram-Schmidt process. Show that $\mathcal{U}$ is a complete set in $L^2[0,1]$. 
Cover Sheet – Numerical Analysis Part

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Name___________________________________________
Problem 1. Let $f$ be a given function in $L^2(0, 2)$ and $u \in H^1(0, 2)$ be the solution of

\begin{equation}
(a(u, v) := \int_0^2 (u'v' + xuv)dx = \int_0^2 fvdx =: L(v), \quad \text{for all } v \in H^1(0, 2).)
\end{equation}

(a) Derive the strong form of problem (1.1) assuming that the solution $u$ is smooth.
(b) Show that the bilinear form $a(\cdot, \cdot)$ is coercive in $H^1(0, 2)$. You first prove that for $v \in H^1(0, 2)$

\begin{equation}
\|v\|_{L^2(0, 2)}^2 \leq C \left( \int_1^2 v^2(x)dx + \|v'\|_{L^2(0, 2)}^2 \right)
\end{equation}

with some positive constant $C$ and then show that the left hand side of this inequality is bounded by $a(v, v)$.
(c) Let $T_h$, $0 < h < 1$, be quasi-uniform partition of $(0, 2)$. The elements of this partitioning will be denoted by $\tau$. Set

\[ V_h := \{ v_h \in H^1(0, 2) : v_h|_\tau \in \mathbb{P}^1, \quad \tau \in T_h \} \]

where $\mathbb{P}^1$ denotes the space of linear polynomials on $\mathbb{R}^2$ and consider the following Galerkin FEM: find $u_h \in V_h$ such that

\begin{equation}
(a_h(u_h, v_h) := \int_0^2 u_h'v_h' + Q_h(xu_hv_h) = L(v_h), \quad \forall v_h \in V_h.)
\end{equation}

where for computing the integral $\int_0^2 xu_hv_h dx$ we have used the quadrature

\[ Q_h(w) := \sum_{\tau \in T_h} \frac{1}{2} (w(P_1) + w(P_2)) \]

with $P_1$ and $P_2$ being the end points of the subinterval $\tau$.

Using similar argument as in the proof of the inequality (1.2), show that $a_h(\cdot, \cdot)$ is coercive in $H^1(0, 2)$, i.e. there is a constant $\alpha_0 > 0$, independent of $h$, such that

\[ a_h(v_h, v_h) \geq \alpha_0 \|v_h\|_{H^1(0, 2)}^2 \quad \forall v_h \in V_h. \]

Problem 2. Let $\Omega \subset \mathbb{R}^2$ be a convex polygonal domain, and let $T_h$ be a shape-regular and quasi-uniform triangulation of $\Omega$ with element diameters uniformly equivalent to $h$. Let also $V_h \subset H^1_0(\Omega)$ be a piecewise linear Lagrange finite element space. You may assume the existence of an interpolation operator $I_h : H^1_0(\Omega) \rightarrow V_h$ satisfying

\[ \|u - I_h u\|_{L^2(\Omega)} + h \|u - I_h u\|_{H^1(\Omega)} \leq C h^2 |u|_{H^2(\Omega)}. \]

(a) Let $u(t) \in H^1_0(\Omega)$ ($0 \leq t \leq T$), $u_0$, and $f$ be sufficiently smooth such that

\[ \int_\Omega u_t v \, dx + \int_\Omega \nabla u \cdot \nabla v \, dx = \int_\Omega f v \, dx, \quad v \in H^1_0(\Omega), \quad 0 < t \leq T; \]

\[ u(x, 0) = u_0(x), \quad x \in \Omega. \]
Write down the spatially semidiscrete (i.e., discretized in space but not in time) finite element formulation of this problem. Denote by $u_h$ the solution to these finite element equations.

(b) For $0 < t \leq T$, let now $\tilde{u}_h(t)$ be the elliptic finite element approximation to $u(t)$. That is
\[ \int_{\Omega} \nabla \tilde{u}_h(t) \cdot \nabla v_h \, dx = \int_{\Omega} \nabla u(t) \cdot \nabla v_h \, dx, \quad v_h \in V_h. \]

Prove that
\[ \int_{\Omega} (u_h - \tilde{u}_h)_t v_h \, dx + \int_{\Omega} \nabla (u_h - \tilde{u}_h) \cdot \nabla v_h \, dx = \int_{\Omega} (u - \tilde{u}_h)_t v_h \, dx, \quad v_h \in V_h, \quad 0 < t \leq T. \]

(c) Next recall Gronwall’s Lemma, which states that if $\sigma$ and $\rho$ are continuous real functions with $\sigma \geq 0$ and $c \geq 0$ is a constant, and if
\[ \sigma(t) \leq \rho(t) + c \int_0^t \sigma(s) \, ds, \quad t \in [0, T], \]
then
\[ \sigma(t) \leq e^{ct} \rho(t), \quad t \in [0, T]. \]

Using this result, prove that
\[ \|(u_h - \tilde{u}_h)(T)\|_{L_2(\Omega)}^2 \leq C(T) \left( \|(u_h - \tilde{u}_h)(0)\|_{L_2(\Omega)}^2 + \int_0^T \|(u - \tilde{u}_h)_t(s)\|_{L_2(\Omega)}^2 \, ds \right). \]

(d) For the final part you will need the following intermediate result. Given $v \in H^1_0(\Omega) \cap H^2(\Omega)$, let $v_h \in V_h$ satisfy
\[ \int_{\Omega} \nabla v_h \cdot \nabla w_h \, dx = \int_{\Omega} \nabla v \cdot \nabla w_h \, dx, \quad \text{all } w_h \in V_h. \]

Then
\[ \|v - v_h\|_{L_2(\Omega)} \leq C h^2 \|v\|_{H^2(\Omega)}. \]

Assuming this result and additionally that $\|(u - u_h)(0)\|_{L_2(\Omega)} \leq C h^2 \|u(0)\|_{H^2(\Omega)}$, prove that
\[ \|(u - u_h)(T)\|_{L_2(\Omega)} \leq C(T) h^2 \left( |u(0)|_{H^2(\Omega)} + \left( \int_0^T |u_t|^2_{H^2(\Omega)} \right)^{1/2} \right). \]

**Problem 3.** Let $(\tau, P^3, \Sigma)$ be a finite element, where $\tau$ is a triangle with vertexes $P_1$, $P_2$, and $P_3$, $P^3$ is the set of cubic polynomials, and $\Sigma$ is the set of degrees of freedom that consists of the values at 9 points on the boundary, namely, three vertexes and two additional points on each side of $\tau$, chosen in such way that together with the vertexes the four points are equally spaced on the side. The tenth degree of freedom is the average of the function over the triangle normalized by the area of the triangle. This means that the ”nodal” basis function $\phi_{10}$ corresponding to this ”degree of freedom” should be zero on the boundary of $\tau$ and should satisfy $\frac{1}{|\tau|} \int_{\tau} \phi_{10} dx = 1$. Find $\phi_{10}$ and the nodal basis functions of this element corresponding to the vertex $P_1$.

**Hint:** Use homogeneous (area) coordinates $\lambda_1$, $\lambda_2$, and $\lambda_3$. 

2