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Here everything can be written down that helps with understanding the Non-Linear Wave Equations Lecture and solving the exercises.

1 Norms

Definition 1 (Sobolev space). *The following is called Sobolev space:*

$$W^{k,p}(\Omega) = \{u \in L^p(\Omega) \mid \forall \alpha \in \mathbb{N}^n, |\alpha| \leq k : \exists D^\alpha u \in L^p(\Omega)\} \quad (1)$$

with the Sobolev Norm, if $p < \infty$:

$$\|u\|_{W^{k,p}(\Omega)} = \left(\sum_{|\alpha| \leq k} \|\partial^\alpha u\|_{L^p(\Omega)}^p \right)^{\frac{1}{p}} \quad (2)$$

and if $p = \infty$:

$$\|u\|_{W^{k,p}(\Omega)} = \max_{|\alpha| \leq k} \|\partial^\alpha u\|_{L^\infty(\Omega)}. \quad (3)$$

Notation:

$$H^k(\Omega) := W^{k,2}(\Omega) \quad (4)$$

$W^{k,p}(\Omega)$ is a Banach space. $C^{k,p}(\Omega)$ is a dense subset of $W^{k,p}(\Omega) \subset L^p(\Omega)$. $H^k(\Omega)$ is a Hilbertspace.

Definition 2 (fractional Sobolev space; source: exercise session 1). *For $s \in \mathbb{R}$ (?) $H^s(\mathbb{R}^n)$ is the completion of $C_0^\infty(\mathbb{R}^n)$ with respect to the norm*

$$\|f\|_{H^s(\mathbb{R}^n)} = \|(1 + |\xi|^2)^{\frac{s}{2}} \mathcal{F}(f)\|_{L^2(\mathbb{R}^n)} \quad (5)$$

where $(1 + |\xi|^2)^{\frac{s}{2}}$ corresponds to a derivative in physical space.

2 Functional Analysis Theorems

Definition 3 (adjoint operator). *The adjoint of a (bounded, linear) operator $T : X \rightarrow Y$ is defined by*

$$T^* : Y \rightarrow X, \langle Tx, y \rangle = \langle x, T^*y \rangle. \quad (6)$$

We have that $T^{**} = T$ and $\|T\| = \|T^*\|$. (letzte Aussage überprüfen)

Theorem 4 (Gronwall's Lemma). *Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be a non-negative continuous function and $g : \mathbb{R} \rightarrow \mathbb{R}$ be a non-negative integrable function such that*

$$f(t) \leq A + \int_0^t f(s)g(s)ds \quad (7)$$

holds for some $A \geq 0$ for every $t \in [0, T]$. Then

$$f(t) \leq A \exp\left(\int_0^t g(s) ds\right) \quad (8)$$

holds for every $t \in [0, T]$.

Theorem 5 (Hahn-Banach). *Let ϕ be a bounded linear functional on a subspace M of a normed (real) vectorspace X . Then there exists a bounded linear functional Φ on X which is an extension of ϕ to X and has the same norm, i.e.*

$$\|\Phi\|_X = \|\phi\|_M, \quad (9)$$

where

$$\|\Phi\|_X = \sup_{x \in X, \|x\|=1} |\Phi(x)|, \|\phi\|_M = \sup_{x \in M, \|x\|=1} |\phi(x)|. \quad (10)$$

Theorem 6 (Arzelà-Ascoli theorem, source: Wiki). *Consider a sequence of functions (f_n) defined on a compact interval. If this sequence is uniformly bounded and uniformly equicontinuous, then there exists a subsequence (f_{n_k}) that converges uniformly.*

Definition 7 (uniformly equicontinuous). *A sequence of functions (f_n) is said to be uniformly equicontinuous if, for every $\varepsilon > 0$, there exists a $\delta > 0$ such that*

$$|f_n(x) - f_n(y)| < \varepsilon \quad (11)$$

whenever $|x - y| < \delta$ for all functions f_n in the sequence.

This is the version of Arzelà-Ascoli used on example sheet 6, problem*, in a specific norm:

Theorem 8 (Arzelà-Ascoli theorem, source: solution to sheet 5). *Suppose there is a sequence (of solutions) $(\phi^{(i)})$ in $C^{k-1}([0, T] \times \mathbb{R}^n)$ that converges to ϕ in a $C^{k-1}([0, T] \times \mathbb{R}^n)$ -sense and is uniformly bounded, meaning $\|\partial^k \phi\|_{L^\infty} \leq A$ (A not dependent on i).*

Then, there exists a subsequence $(\phi^{(i_\lambda)})$ that converges in $C^k([0, T] \times \mathbb{R}^n)$.

Theorem 9 (Banach-Alaoglu).

Definition 10 (Weak Convergence; source: Wiki). *A sequence of elements (x_n) in a Hilbert space H is said to converge weakly to $x \in H$ if*

$$\langle x_n, y \rangle \rightarrow \langle x, y \rangle \quad (12)$$

for all $y \in H$, $\langle \cdot, \cdot \rangle$ denoting the inner product of H .

Notation: $x_n \rightharpoonup x$

Theorem 11 (Riesz Representation thm).

3 Fourier Transformation

Open Question: What is the advantage of Fourier representation?

Definition 12 (Schwartz space). *The Schwartz space $\mathcal{S}(\mathbb{R}^n)$ is a vectorspace given by*

$$\mathcal{S}(\mathbb{R}^n) = \{f \in C^\infty(\mathbb{R}^n) | \forall \alpha, \beta \in \mathbb{N}_0^n, \sup_{x \in \mathbb{R}^n} |x^\alpha \partial^\beta f(x)| < \infty\} \quad (13)$$

equipped with a countable family of semi-norms

$$\|f\|_{\alpha, \beta} := \sup_{x \in \mathbb{R}^n} |x^\alpha \partial^\beta f(x)|. \quad (14)$$

You can think of the Schwartz space as functions that decay faster than any polynomial.

Definition 13 (Fourier transform). *Given a function $f \in \mathcal{S}(\mathbb{R}^n)$, we define the Fourier transform by*

$$\mathcal{F}(f)(\xi) := \int_{\mathbb{R}^n} f(x) e^{-2\pi i x \cdot \xi} dx. \quad (15)$$

The inverse Fourier transform is given by

$$\mathcal{F}^{-1}(f)(\xi) := \int_{\mathbb{R}^n} f(x) e^{+2\pi i x \cdot \xi} dx. \quad (16)$$

Theorem 14 (properties of Fourier transform and norms; source: exercise session 1). *For $f \in \mathcal{S}(\mathbb{R}^n)$ the following holds:*

1. $\|\mathcal{F}(f)\|_{L^2(\mathbb{R}^n)} = \|f\|_{L^2(\mathbb{R}^n)}$
2. $\|\mathcal{F}(f)\|_{L^\infty(\mathbb{R}^n)} = \|f\|_{L^1(\mathbb{R}^n)}$

Theorem 15 (properties of the Fourier transform; source: exercise session 1). *For $f \in \mathcal{S}(\mathbb{R}^n)$ the following properties hold:*

1. $\mathcal{F}(\partial_i f(x)) = 2\pi i \xi_i \mathcal{F}(f)(\xi)$
2. $\mathcal{F}(x_i f(x)) = -\frac{1}{2\pi i} \partial_{\xi_i} \mathcal{F}(f)(\xi)$

4 Important Inequalities

Theorem 16 (The interpolation inequality). *We have*

$$\|f\|_{H^s(\mathbb{R}^n)} \leq C(s_1, s_2, s_n) \|f\|_{H^{s_1}(\mathbb{R}^n)}^{\theta_1} \|f\|_{H^{s_2}(\mathbb{R}^n)}^{\theta_2}, \quad (17)$$

where $0 \leq s_1 \leq s \leq s_2$, $\theta_1 + \theta_2 = 1$ and $\theta_1 s_1 + \theta_2 s_2 = s$.

4.1 Sobolev Embedding

Theorem 17 (Sobolev embedding thm; source: sheet 1). *There exists a constant $C = C(n, s) > 0$ such that for every $f \in H^s(\mathbb{R}^n)$ with $s > \frac{n}{2}$ we have*

$$\|f\|_{L^\infty(\mathbb{R}^n)} \leq C\|f\|_{H^s(\mathbb{R}^n)}. \quad (18)$$

Theorem 18 (source: sheet 1). *If s is a non-negative integer, there exists a constant $C = C(s)$ such that for every $f \in H^s(\mathbb{R}^n)$ with $s > \frac{n}{2}$ we have*

$$\frac{1}{C} \sum_{|\alpha| \leq s} \|\partial^\alpha f\|_{L^2(\mathbb{R}^n)} \leq \|f\|_{H^s(\mathbb{R}^n)} \leq C \sum_{|\alpha| \leq s} \|\partial^\alpha f\|_{L^2(\mathbb{R}^n)}. \quad (19)$$

Theorem 19. *Sobolev inequality with $C^2(\mathbb{R}^n)$ used in Problem*, sheet 6. Not found...*

Theorem 20 (second Sobolev embedding thm; source: Wiki). *If $n < pk$ and $r + \alpha = k - \frac{n}{p}$ with $\alpha \in (0, 1)$, then one has the embedding*

$$W^{k,p}(\mathbb{R}^n) \subset C^{r,\alpha}(\mathbb{R}^n). \quad (20)$$

5 Basic Analysis, Measure Theory

Theorem 21 (Young's Inequality). *Let p and q be positive real numbers such that $\frac{1}{p} + \frac{1}{q} = 1$. Then, for any non-negative a and b it holds*

$$ab \leq \frac{a^p}{p} + \frac{b^q}{q}. \quad (21)$$

Theorem 22 (Young's Inequality Special case). *Let $x, y \in \mathbb{R}^n$, $\delta > 0$, $p, q > 1$ such that $\frac{1}{p} + \frac{1}{q} = 1$. Then we have*

$$|xy| \leq \delta|x|^2 + \frac{1}{4\delta}|y|^2. \quad (22)$$

Theorem 23 (Hölder's Inequality; source: Wiki). *Let p and q be positive real numbers such that $\frac{1}{p} + \frac{1}{q} = 1$. Then, if $f \in L^p$ and $g \in L^q$:*

$$\|fg\|_{L^1} \leq \|f\|_{L^p} \|g\|_{L^q}. \quad (23)$$

Theorem 24 (Lebesgue Monotone Convergence; source: math3ma.com). *Suppose $(f_n : X \rightarrow [0, \infty))$ being a monotonically increasing sequence of measurable functions on a measurable set X such that $f_n \rightarrow f$ pointwise almost everywhere, then*

$$\lim_{n \rightarrow \infty} \int_X f_n = \int_X f. \quad (24)$$

Theorem 25 (Fatou's Lemma; source: Wiki). *Given a measure space $(\Omega, \mathcal{F}, \mu)$ and a set $X \in \mathcal{F}$, let $(f_n : X \rightarrow [0, \infty])$ be a sequence of measurable functions. Define the function $F_X : X \rightarrow [0, \infty]$ by setting $f(x) = \liminf_{n \rightarrow \infty} f_n(x)$ for every $x \in X$.*

Then f is measurable, and also

$$\int_X f d\mu \leq \liminf_{n \rightarrow \infty} \int_X f_n d\mu \quad (25)$$

where the integrals may be infinite.

Theorem 26 (Change of Variables Formula; source: Wiki). *Let $\Omega \subset \mathbb{R}^n$ be an open set, $\Phi : \Omega \rightarrow \Phi(\Omega) \subset \mathbb{R}^n$ a diffeomorphism. A function f is integrable on $\Phi(\Omega)$ iff the function $x \mapsto f(\Phi(x))|Det(D\Phi(x))|$ is integrable on Ω . Then we have*

$$\int_{\Phi(\Omega)} f(y) dy = \int_{\Omega} f(\Phi(x)) |\det(D\Phi(x))| dx. \quad (26)$$

Theorem 27 (Picard-Lindelöf). *Let $G \subset \mathbb{R} \times \mathbb{R}^n$ be open and $f : G \rightarrow \mathbb{R}^n$ a continuous function satisfying a Lipschitz property locally. Then for every $(a, c) \in G$ there exists a $\epsilon > 0$ and a solution*

$$\phi : [a - \epsilon, a + \epsilon] \rightarrow \mathbb{R}^n \quad (27)$$

for the ODE $y' = f(x, y)$ with initial data $\phi(a) = c$.