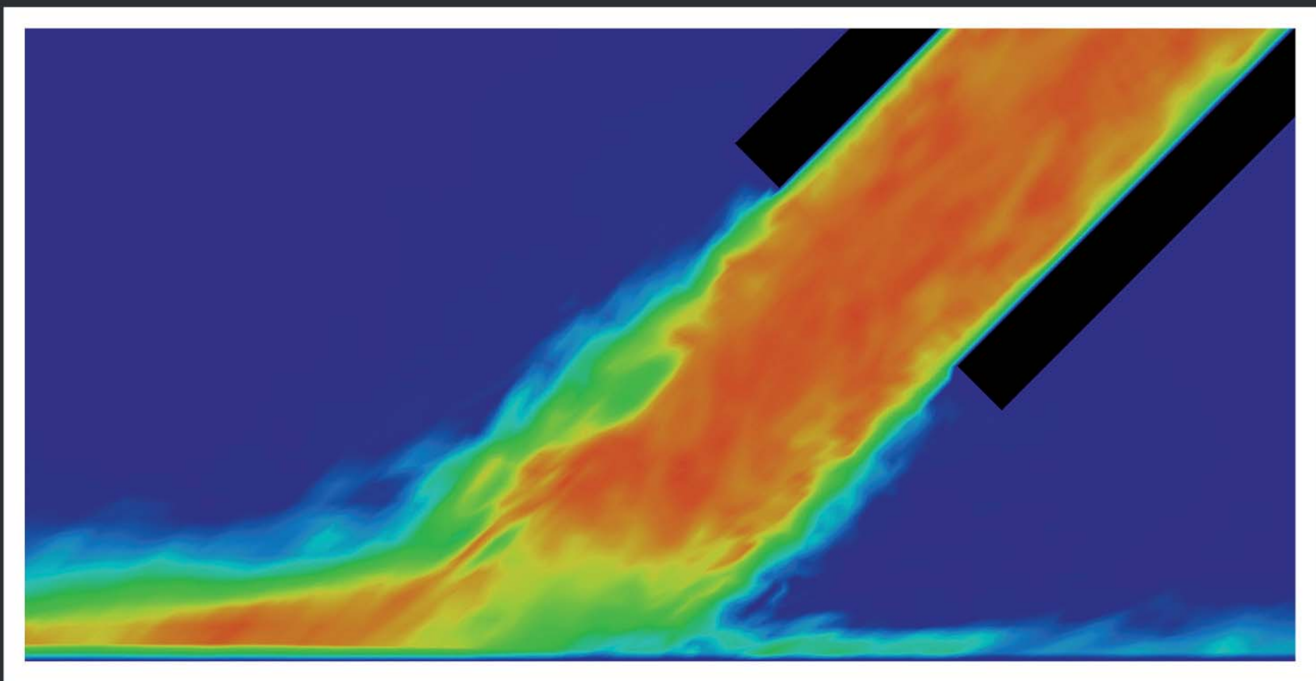
Kristofer Leach

# Modelling Force Transfer in Boundary Layers of Moving Walls for Compressible and Incompressible Turbulent Flows Across Multiple Scales



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# Modelling Force Transfer in Boundary Layers of Moving Walls for Compressible and Incompressible Turbulent Flows Across Multiple Scales

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von
M.Math. Kristofer Leach

Gutachter:
Prof. Dr. rer. nat. Claus Braxmaier
Prof. Dr. rer. nat. Thomas Schuster, Universität des Saarlandes

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# Zusammenfassung

Die Entwicklung kleiner Werkzeugmaschinen zur Bearbeitung extrem kleiner Werkstücke ist u.a. auf den Gebieten der Mechantronik, der Optik oder der Medizin von zunehmend größerer Bedeutung. Das Miniaturisieren existierender Werkzeuge stößt allmählich an gewisse Grenzen und es ist nötig, neue Werkzeuge zu entwickeln, um einen Fortschritt zu erzielen.

Diese Arbeit beschreibt die Gestaltung einer neuartigen Schleifkugel, die magnetisch gelagert und von einer pressluftgetriebenen Strömung in Rotation versetzt wird. Es wird eine Parameterstudie durchgeführt, welche die optimale geometrische Auslegung eines Prototyps unter Einhaltung gewisser physikalischer Einschränkungen bestimmt. Die daraus hervorgehende optimale Auslegung wird im Anschluss detailliert untersucht, um festzustellen, welcher Belastung die elektromagnetische Lagerung standzuhalten hat und um die zum Schleifen verfügbare Kraft zu quantifizieren. Entgegen den Erwartungen zeigte die Untersuchung, dass Luft kein geeignetes Antriebsmedium darstellt und dass Öl an dessen Stelle treten muss um genügend Schleifkraft zu erzielen. Die bei der Entwicklung des Prototyps gesammelten Erfahrungen dienen als Grundlage für die Entwicklung eines kleineren funktionsfähigen Schleifwerkzeugs, welches unter Verwendung von hydraulischem Antrieb analysiert wird. Im Anschluss wird unter Verwendung von Luftantrieb eine skalenübergreifende Analyse der auf die Schleifkugel wirkenden Kräfte durchgeführt.

Machzahlen betragen bis zu 0,9, während Reynoldszahlen maximal $10^5$ erreichen. Daher wird Large-Eddy-Simulation in Verbindung mit dem kompressiblen Smagorinsky Modell nach Furby eingesetzt. Geringe Temperaturvariation erlaubt die Annahme adiabater Wände. Fluid-Struktur Interaktion wird durch das logarithmische Wandgesetz für kompressible turbulente Strömungen modelliert. Die Parameterstudien untersuchen den Einfluss verschiedener Faktoren wie geometrische Eigenschaften und Viskosität des Antriebsmediums. Anschließend werden Simulationen unter einer Vielzahl verschiedener Normvolumenströme $\dot{V}_N$ und Kugelrotationsfrequenzen $f$ durchgeführt.

Da die Schleifkraft des 40 mm Prototyps weniger als 0,04 N betrug, wurde für ein funktionstüchtiges 8 mm Schleifwerkzeug das Antriebsmedium durch ein Öl mit einer kinematischen Viskosität von $1{,}38 \cdot 10^4\,\mathrm{m^2\,s^{-1}}$ bei Raumtemperatur ersetzt. Zwei weitere Kanäle wurden hinzugefügt und vertikal angeordnet, um die Schleifkraft und die Anpresskraft zu erhöhen. So konnte ausreichend Schleifkraft von mehr als 0,1 N und Anpresskraft von mehr als 1 N erzielt werden. Im Anschluss wurden durch eine Skalenanalyse dimen-

sionslose Gleichungen für Normalkräfte, Schleifkraft sowie Anpresskraft aufgestellt. Diese konnten nicht nur genutzt werden um auf beliebige weitere Skalen schließen zu können, sondern auch um die beiden Antriebsmedien und die beiden Geometrien untereinander zu vergleichen.

Die in dieser Arbeit präsentierten Ergebnisse zeigen nicht nur wie die Kraftübertragung von Fluiden auf Festkörper skalenübergreifend modelliert werden kann und die Resultate zur Herleitung dimensionsloser Gleichungen, welche für beliebige Parameter gelten, genutzt werden, sondern bieten eine Grundlage für die Entwicklung eines neuartigen und bahnbrechenden Schleifwerkzeuges auf dem Gebiet des Mikroschleifens.

# Abstract

Developing miniature tools used to machine parts that are themselves small in size is rapidly gaining importance in fields such as mechatronics, optics, or medicine. Miniaturising existing tools has its limitations and it is becoming ever more necessary to develop new tools in order make progress in this regard.

This thesis describes the design of a new kind of abrading sphere which is magnetically mounted inside a spherical gap and set in rotation pneumatically with air. A parametric study is performed in order to determine optimal geometric layout of a prototype while taking physical restrictions into account. The resulting optimal configuration is then examined in detail in order to determine demands to be met by the magnetic bearing and its computerised control, as well as to quantify the extent of force potentially available to the abrasion process. Contrary to expectation, the analysis showed that air is not a viable propulsion medium and that oil needs to take its place to yield sufficient grinding force. Using the knowledge gained from developing the prototype, a smaller working model is devised and analysed using hydraulic propulsion. Use of the tool with pneumatic propulsion is then subjected to a study across multiple length scales focusing on the forces acting on the grinding sphere.

Mach numbers range up to 0.9 with Reynolds numbers of up to $10^5$. Hence, Large Eddy Simulation is performed in conjunction with the compressible Smagorinsky model according to Fureby. Minimal temperature variation allows for the assumption of adiabatic walls. Fluid-solid interaction is modelled using the law of the wall for compressible turbulent flow. Parametric studies investigate the influence of varying geometric factors and viscosities of the fluid used. Subsequently, simulations are conducted under a variety of standard volumetric flow rates $\dot{V}_N$ and rotation frequencies $f$.

The available grinding force determined for the 40 mm prototype using pneumatic propulsion was found not to exceed 0.04 N. For the working 8 mm model, the propulsion medium was thus changed to an oil with a kinematic viscosity of $1.38 \cdot 10^{-4}\,\mathrm{m}^2\,\mathrm{s}^{-1}$ at room temperature. Two additional fluid ducts were added and introduced vertically from the top to increase grinding force and downward force. Sufficient grinding force in excess of 0.1 N and contact force exceeding 1 N could be achieved. In a subsequent study across multiple scales, non-dimensional relations governing normal forces, grinding force, as well as grinding power were established. These could not only be used to predict arbitrary scales, but also to compare the two propulsion media and geometric variations with each other.

The results presented in this thesis demonstrate how fluid-to-solid force transfer can be modelled across a multitude of scales and the results used to derive non-dimensional relations that hold true for arbitrary parameters. They also lay the foundation for the development of a novel and revolutionary grinding tool in the field of miniature precision machining.

# Preface

I would like to extend my gratitude to my project supervisors the late Prof. Dr.-Ing. Hans J. Rath, Prof. Dr. Claus Braxmaier, and Dr.-Ing. Rodion Groll for their continued support and their valuable and inspiring guidance in the field of Fluid Mechanics and CFD. Also, I would like to thank Prof. Dr. Thomas Schuster, Prof. Dr.-Ing. Ekkard Brinksmeier, Prof. Dr.-Ing. Bernd Orlik, Dr.-Ing. Ralf Gläbe, Dr.-Ing. Lars Schönemann, Carla Brandao, Alexander Norbach, and all the members of SPP 1476 for their excellent cooperation and fruitful discussions while working on project *GrindBall*. Additionally, I would like to thank my colleagues at ZARM Stephan Reichel, Claudia Zimmermann, Torben Schadowski, Fabian Fastabend, Rico Schultz, and Želimir Marojević with whom I had inspiring scientific inter-exchange throughout my time there. I would especially like to thank the members of my family Barry, Helga, and Jennifer for their love and support.

Furthermore, many thanks are due to the German Research Foundation (DFG) for funding project *GrindBall* and the North-German Supercomputing Alliance (HLRN) for providing free access to their super-computing facilities, thereby enabling a quality of simulations that would not have been achievable by regular means.

# Contents

# Nomenclature

Scalar quantities are dented by normal italic symbols while vectors and tensors are presented in bold. To differentiate, vectors are underlined once while tensors receive double underlining. Alternatively, Einstein notation may be used to denote vector and tensor components. Unless stated otherwise, units and dimensions are presented according to the International System of Units, i.e. mass (M) in kg, length (L) in meters m, time (T) in seconds s, temperature (Θ) in Kelvin K, and amount of substance (N) in mol. Furthermore, the derived units Newton N=kg m s$^{-2}$, Pascal Pa=kg m$^{-1}$ s$^{-2}$, Hertz Hz=s$^{-1}$, Joule J=kg m$^{2}$ s$^{-2}$and Watt W=J s$^{-1}$are employed.

## Roman Symbols

| Symbol | Description | Unit | Dimension |
|---|---|---|---|
| $A$ | Area | m$^2$ | L$^2$ |
| $A_S$ | Sutherland coefficient | kg m$^{-1}$s$^{-1}$K$^{-\frac{1}{2}}$ | M L$^{-1}$T$^{-1}$Θ$^{-\frac{1}{2}}$ |
| $\underline{\mathbf{a}}$ | Acceleration | m s$^{-2}$ | L T$^{-2}$ |
| $a$ | Speed of sound | m s$^{-1}$ | L T$^{-1}$ |
| $a$ | Arbitrary scalar | | |
| $B$ | Constant | | |
| $\underline{\mathbf{b}}$ | Body force vector | N | M L T$^{-2}$ |
| $b$ | Blending coefficient | | |
| $C_{ij}$ | Clark tensor | m$^2$s$^{-2}$ | L$^2$T$^{-2}$ |
| $C$ | Constant | | |
| $c_p$ | Specific heat at constant pressure | J kg$^{-1}$K$^{-1}$ | L$^2$Θ$^{-1}$T$^{-2}$ |
| $c_v$ | Specific heat at constant volume | J kg$^{-1}$K$^{-1}$ | L$^2$Θ$^{-1}$T$^{-2}$ |
| $d$ | Diameter | m | L |
| $E$ | Energy | J | M L$^2$T$^{-3}$ |
| $E_{\mathrm{tot}}$ | Total energy per unit volume | J m$^{-3}$ | M L$^{-1}$T$^{-2}$ |
| $\underline{\mathbf{e}}_i$ | Unit vector | | |
| $e$ | Internal energy per unit mass | m$^2$s$^{-2}$ | L$^2$T$^{-2}$ |
| $\underline{\mathbf{F}}$ | Force | N | M L T$^{-2}$ |
| $\underline{\mathbf{f}}$ | Force per volume | N m$^{-3}$ | M L$^{-2}$T$^{-2}$ |
| $F_t$ | Abrasion force | N | M L T$^{-2}$ |
| $f$ | Rotation frequency | Hz | T$^{-1}$ |
| $f$ | Generic flux term | | |
| $f$ | Arbitrary function | | |
| $G$ | Convolution kernel | | |
| $\underline{\mathbf{g}}$ | Gravity vector | m s$^{-2}$ | L T$^{-2}$ |
| $h$ | Enthalpy per unit mass | m$^2$s$^{-2}$ | L$^2$T$^{-2}$ |

| | | | |
|---|---|---|---|
| $h$ | Height | m | L |
| $\mathbf{I}$ | Identity tensor | | |
| $K$ | Constant | | |
| $K_B$ | Boltzmann Constant | $\mathrm{J\,K^{-1}}$ | $\mathrm{M\,L^{2}\Theta^{-1}T^{-2}}$ |
| $k$ | Thermal conductivity | $\mathrm{W\,m^{-1}K^{-1}}$ | $\mathrm{M\,L\,\Theta^{-1}T^{-3}}$ |
| $k_l$ | Characteristic length of wall roughness | m | L |
| $k_{\mathrm{sgs}}$ | Subgrid scale kinetic energy | $\mathrm{m^{2}s^{-2}}$ | $\mathrm{L^{2}T^{-2}}$ |
| $L_{ij}$ | Leonard tensor | $\mathrm{m^{2}s^{-2}}$ | $\mathrm{L^{2}T^{-2}}$ |
| $L$ | Characteristic length | m | L |
| $\underline{\mathbf{M}}$ | Moment | $\mathrm{N\,m}$ | $\mathrm{M\,L^{2}T^{-2}}$ |
| $M$ | Molecular weight | $\mathrm{kg\,mol^{-1}}$ | $\mathrm{M\,N^{-1}}$ |
| $m$ | Mass | kg | M |
| $\dot{m}$ | Mass flow rate | $\mathrm{kg\,s^{-1}}$ | $\mathrm{M\,T^{-1}}$ |
| $\underline{\mathbf{n}}$ | Normal vector | | |
| $P$ | Power | W | $\mathrm{M\,L\,T^{-3}}$ |
| $p$ | Pressure | Pa | $\mathrm{M\,L^{-1}T^{-2}}$ |
| $Q$ | Source term | | |
| $Q$ | Heat per unit volume | $\mathrm{J\,m^{-3}}$ | $\mathrm{M\,L^{-1}T^{-2}}$ |
| $\underline{\mathbf{q}}$ | Heat flux | $\mathrm{kg\,s^{-2}}$ | $\mathrm{M\,T^{-3}}$ |
| $R_{ij}$ | Reynolds tensor | $\mathrm{m^{2}s^{-2}}$ | $\mathrm{L^{2}T^{-2}}$ |
| $R$ | Specific gas constant | $\mathrm{J\,kg^{-1}K^{-1}}$ | $\mathrm{L^{2}\Theta^{-1}T^{-2}}$ |
| $R_0$ | Universal gas constant | $\mathrm{J\,mol^{-1}K}$ | $\mathrm{M\,L^{2}N^{-1}\Theta^{-1}T^{-2}}$ |
| $\underline{\mathbf{r}}$ | Spatial position vector | | |
| $r$ | Radial vector | | |
| $r$ | Radius | m | L |
| $\underline{\underline{\mathbf{S}}}$ | Symmetric velocity gradient | $\mathrm{s^{-1}}$ | $\mathrm{T^{-1}}$ |
| $s$ | Path length | m | L |
| $\underline{\underline{\mathbf{T}}}$ | Arbitrary tensor | | |
| $\underline{\underline{\mathbf{U}}}$ | Arbitrary tensor | | |
| $T$ | Temperature | K | $\Theta$ |
| $T_S$ | Sutherland constant | K | $\Theta$ |
| $t$ | Time | s | T |
| $U$ | Magnitude of velocity | $\mathrm{m\,s^{-1}}$ | $\mathrm{L\,T^{-1}}$ |
| $\underline{\mathbf{u}}$ | Velocity vector | $\mathrm{m\,s^{-1}}$ | $\mathrm{L\,T^{-1}}$ |
| $u_\tau$ | Shear velocity | $\mathrm{m\,s^{-1}}$ | $\mathrm{L\,T^{-1}}$ |
| $u_1, u_2, u_3$ | Velocity components | $\mathrm{m\,s^{-1}}$ | $\mathrm{L\,T^{-1}}$ |
| $\underline{\mathbf{v}}$ | Arbitrary vector | | |
| $V$ | Volume | $\mathrm{m^{3}}$ | $\mathrm{L^{3}}$ |
| $\dot{V}$ | Volumetric flow rate | $\mathrm{m^{3}s^{-1}}$ | $\mathrm{L^{3}T^{-1}}$ |
| $\underline{\mathbf{w}}$ | Rate of work per unit area | $\mathrm{kg\,s^{-2}}$ | $\mathrm{M\,T^{-3}}$ |
| $\underline{\mathbf{w}}$ | Arbitrary vector | | |

| | | | |
|---|---|---|---|
| $W$ | Work per unit volume | $\mathrm{J\,m^{-3}}$ | $\mathrm{M\,L^{-1}T^{-2}}$ |
| $\underline{\mathbf{x}}$ | Spatial position vector | | |
| $\hat{\mathbf{x}}$ | Unit vector | | |
| $x$ | Standard variable | | |
| $x_1, x_2, x_3$ | Cartesian coordinates | | |
| $x, y, z$ | Cartesian coordinates | | |

## Greek Symbols

| Symbol | Description | Unit | Dimension |
|---|---|---|---|
| $\alpha$ | Thermal diffusivity | $\mathrm{Pa\,s}$ | $\mathrm{M\,L^{-1}T^{-1}}$ |
| $\alpha$, $\beta$, $\gamma$ | Direction cosines | | |
| $\alpha$, $\beta$ | Angles | | |
| $\beta$ | Coefficient of thermal expansion | $\mathrm{K^{-1}}$ | $\Theta^{-1}$ |
| $\Gamma$ | Diffusion coefficient | $\mathrm{kg\,m^{-1}s^{-1}}$ | $\mathrm{M\,L^{-1}T^{-1}}$ |
| $\gamma$ | Ratio of specific heats | | |
| $\delta$ | Viscous sublayer thickness | $\mathrm{m}$ | $\mathrm{L}$ |
| $\delta_{ij}$ | Kronecker delta | | |
| $\Delta$ | Difference | | |
| $\overline{\Delta}$ | Filter cutoff length | $\mathrm{m}$ | $\mathrm{L}$ |
| $\underline{\underline{\boldsymbol{\epsilon}}}$ | Strain rate tensor | $\mathrm{s^{-1}}$ | $\mathrm{T^{-1}}$ |
| $\epsilon$ | Error | | |
| $\overline{\epsilon}$ | Extrapolated standard deviation | | |
| $\theta$ | Angle | | |
| $\kappa$ | Von Kármán Constant | | |
| $\lambda$ | Coefficient of bulk viscosity | $\mathrm{Pa\,s}$ | $\mathrm{M\,L^{-1}T^{-1}}$ |
| $\lambda$ | Interpolation factor | | |
| $\mu$ | Dynamic viscosity | $\mathrm{Pa\,s}$ | $\mathrm{M\,L^{-1}T^{-1}}$ |
| $\nu$ | Kinematic viscosity | $\mathrm{m^2s^{-1}}$ | $\mathrm{L^2T^{-1}}$ |
| $\xi$ | parameter | | |
| $\rho$ | Density | $\mathrm{kg\,m^{-3}}$ | $\mathrm{M\,L^{-3}}$ |
| $\underline{\underline{\boldsymbol{\sigma}}}$ | Stress tensor | $\mathrm{kg\,m^{-1}s^{-2}}$ | $\mathrm{M\,L^{-1}T^{-2}}$ |
| $\sigma$ | Standard deviation | | |
| $\sigma(x)$ | Sigmoid function | | |
| $\underline{\underline{\boldsymbol{\tau}}}$ | Sub-grid scale stress tensor | $\mathrm{m^2s^{-2}}$ | $\mathrm{L^2T^{-2}}$ |
| $\tau$ | Stress | $\mathrm{kg\,m^{-1}s^{-2}}$ | $\mathrm{M\,L^{-1}T^{-2}}$ |
| $\tau_w$ | Wall shear stress | $\mathrm{kg\,m^{-1}s^{-2}}$ | $\mathrm{M\,L^{-1}T^{-2}}$ |
| $\Phi$ | Dissipation function | $\mathrm{N\,s^{-1}}$ | $\mathrm{M\,L\,T^{-3}}$ |
| $\underline{\boldsymbol{\psi}}$ | Arbitrary vector | | |
| $\psi$ | Arbitrary intensive property | | |

| | | | |
|---|---|---|---|
| $d\underline{\boldsymbol{\Omega}}$ | Rotation vector | | |
| $\Omega$ | Control volume | $m^3$ | $L^3$ |
| $\underline{\boldsymbol{\omega}}$ | Vorticity | $s^{-1}$ | $T^{-1}$ |

## Dimensionless quantities

| Symbol | Description | Definition |
|---|---|---|
| $Co$ | Courant number | $\Delta t \sum_{i=1}^{3} \frac{u_i}{\Delta x_i}$ |
| $Pe$ | Péclet number | $\frac{\rho U \Delta x}{2\Gamma}$ |
| $Re$ | Reynolds number | $\frac{UL}{\nu}$ |
| $Re_w$ | Boundary Reynolds number | $\frac{u_\tau k_l}{\nu}$ |
| $u^+$ | Dimensionless velocity | $\frac{u}{u_\tau}$ |
| $u_\tau$ | Shear velocity | $\sqrt{\frac{\tau_w}{\rho}}$ |
| $y^+$ | Wall distance | $\frac{y u_\tau}{\nu}$ |

## Subscripts

| Symbol | Description |
|---|---|
| 0 | Initial value |
| 0 | Zero value |
| $d$ | Duct |
| eff | Effective quantity |
| $g$ | Gap |
| $l$ | Length related quantity |
| $M$ | Mechanical |
| max | maximum |
| min | minimum |
| $o$ | Offset |
| op | operating point |
| $p$ | Pressure |
| $s$ | Sphere |
| sgs | Sub-grid scale |
| $t$ | Tangential |
| $t$ | Turbulent |
| tot | Total |
| $\tau$ | Shear stress related quantity |
| $v$ | Viscous |
| $w$ | Wall related quantity |

## Superscripts

| Symbol | Description |
|---|---|
| $+$ | Wall coordinate |
| $*$ | Deviatoric component |
| $D$ | Dimensionless quantity |
| 1mm | 1 mm sphere |
| 8mm | 8 mm sphere |
| 40mm | 40 mm sphere |
| diff | diffusive |
| num | numerical |
| $p$ | prototype |
| real | realistic |
| $T$ | Transpose |

## Operations

| Operation | Description | Definition |
|---|---|---|
| $\nabla s$ | Gradient of $s$ | $\frac{\partial s}{\partial x_i}\underline{\mathbf{e}}_i$ |
| $\nabla \underline{\mathbf{v}}$ | Gradient of $\underline{\mathbf{v}}$ | $\frac{\partial v_i}{\partial x_j}\left(\underline{\mathbf{e}}_i \otimes \underline{\mathbf{e}}_j\right)$ |
| $\nabla \cdot \underline{\mathbf{v}}$ | Divergence of $\underline{\mathbf{v}}$ | $\frac{\partial v_i}{\partial x_i}$ |
| $\nabla^2 s$ | Laplacian of $s$ | $\frac{\partial}{\partial x_i}\frac{\partial s}{\partial x_i}$ |
| $\underline{\mathbf{v}} \otimes \underline{\mathbf{w}}$ | Outer product of $\underline{\mathbf{v}}$ and $\underline{\mathbf{w}}$ | $T_{ij} = v_i w_j$ |
| $tr(\underline{\underline{\mathbf{T}}})$ | Trace of $\underline{\underline{\mathbf{T}}}$ | $T_{kk}$ |
| $\underline{\underline{\mathbf{T}}}^*$ | Deviatoric component of $\underline{\underline{\mathbf{T}}}$ | $T_{ij} - T_{ii}\delta_{ij}$ |
| $\underline{\underline{\mathbf{T}}} : \underline{\underline{\mathbf{U}}}$ | Double inner product of $\underline{\underline{\mathbf{T}}}$ and $\underline{\underline{\mathbf{U}}}$ | $T_{ij}U_{ij}$ |

## Abbreviations

| Acronym | Description |
|---|---|
| 1D | One-dimensional |
| 2D | Two-dimensional |
| 3D | Three-dimensional |
| CDS | Central differencing scheme |
| DNS | Direct Numerical Simulation |
| FDM | Finite Difference Method |
| FEM | Finite Element Method |
| FVM | Finite Volume Method |
| LES | Large Eddy Simulation |

| | |
|---|---|
| LHS | Left hand side |
| LUDS | Linear Upwind Differencing Scheme |
| RANS | Reynolds-averaged Navier-Stokes |
| RHS | Right hand side |
| sgs | Subgrid scale |
| rpm | Revolutions per minute |
| UDS | Upwind differencing scheme |
| w.r.t. | With respect to |

# List of Figures