A GT-POWER Based Predictive Radial Turbine Model (Progress report)

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Overview of Presentation

1. Introduction
2. Tools for 1-D Simulation of a Radial Turbine
3. Application of 1-D Modules to In-Turbine Flow Simulation
4. Calibration of a 1-D Turbine Model
5. Examples of Results
6. Conclusion and Prospects

Goals:

To simulate interaction between exhaust pressure waves and a turbine.
To extrapolate a turbine map keeping physical meaning of it.
1. Introduction: State-of-the-Art

- Attempts to describe pressure waves at a turbine (or compressor) since 1960’s to present: simple, schematic models using “1D” central streamline w/o realistic geometry.

- “1D” central streamline steady model developed and successfully calibrated (SAE 2002, SAE 2008)

- Measurements at model turbine pulsator testbeds or directly at an engine- use of results with mass/energy accumulation?

- Tools for 3-D CFD simulations – time and computer capacity requirements.

- Tools for 1-D simulations (nearly) ready for application (SAE 2008).
1. Introduction: Motivation

TURBINE PARAMETERS = f(deg CA)

- Isentropic Efficiency $\eta_T$
- Discharge Coefficient $\mu_T$
- Velocity Ratio $x = \frac{u}{c}$

Crank Angle [deg from CTDC]

- $\eta_T$
- $\mu_T$
- $\pi_T$

Medium scales should be addressed.

Heisler, Engine Technology. SAE 1998
1. Introduction: Motivation

Tools for 1-D Simulation of a Radial Turbine

Application of 1-D Modules to In-Turbine Flow Simulation

Calibration of a 1-D Turbine Model

Normalized Velocity Maps of Radial Turbine

Optimum Velocity Ratio

Radial Turbine at High Pressure Ratio

Isentropic Efficiency and Velocity Ratio [1]

Discharge Coefficient : Nozzle Exit Mach Number [1]

Normalized Blade Speed Ratio \( \times / \times_{\text{nom}} \) [1]

Pressure Ratio \( \pi T \) [1]
1. Introduction: Motivation

- More flexible turbine model for different layouts with integrated boost control or EGR suitable at medium time-scale accuracy.

- Integrated WG chamber or outlet diffuser.
1. Introduction: Motivation

- More flexible turbine model for different layouts with integrated boost control or EGR suitable at medium time-scale accuracy.

- Outlet diffuser with unsteady flow.
2. Tools for 1-D Simulation of a Radial Turbine

- Modules and solvers for 1-D “Pipe” with variable cross/section area, source terms for enthalpy and momentum, external acceleration (rotating pipe) and curvature.
- Modules for flow momentum mixing/splitting (“Flow splits”).
- Modules for orifices with variable discharge coefficient/area and sensor/signal processor/actuator chains.
- 1-D central streamline, steady flow turbine model. Definition of loss and flow separation coefficients.
2. Tools for 1-D Simulation of a Radial Turbine

- Modules with external acceleration: splitting an impeller into parts with different orientation to axis of rotation
2. Tools for 1-D Simulation of a Radial Turbine

- Transformation modules must be "programmed" separately to change total enthalpy by a source term (heat transfer) and velocity (piping cross-section) maintaining all static state parameters and mass flow rate.

\[
\frac{\dot{m}_I}{\dot{m}_N} = \Delta m_{I\text{leak}}
\]

\[
\frac{w_{r2I}}{c_{r2I}} = \frac{\dot{m}_I}{\rho_{2N}A_{2N}}
\]

\[
\tan\beta_{2I} = \frac{w_{r2I}}{w_{r2I}} \frac{\tan\alpha_{2N} - w_u}{w_{r2I}}
\]

\[
\Delta H_0 = \dot{m}_I(h_{0\text{rel}} - h_0) = \frac{w_2^2 - c_2^2}{2} = -\dot{m}_I \frac{w_r^2}{2}(\tan^2 \alpha_{2N} - \tan^2 \beta_{2I})
\]
2. Tools for 1-D Simulation of a Radial Turbine

\[ m = A_2 \rho_2 w_{2s} = (C_D A_{geom2}) \rho_2 (\eta w_{2s}) \]

\[ \frac{w_{2s}^2}{2} = h_{01} - h_{2s} = h_{01} - h_2 + \Delta h_{lost} = \frac{h_{01} - h_2}{\eta} = \frac{w_2^2}{2\eta} \]

\[ \Delta h_{lost} = c_p T_{01} \left[ 1 - \left( \frac{p_{02}}{p_{01}} \right)^{\frac{k-1}{k}} \right] = \frac{C_p}{2} w_2^2 \]

\[ \eta = \frac{1}{1 + C_p} \; ; \; \quad C_D = \sqrt{\eta} \]
2. Tools for 1-D Simulation of a Radial Turbine

- Modules and solvers for 1-D “Pipe” with variable cross/section area, source terms for enthalpy and

\[ w_{ref} = \frac{m_I}{A_{ref} \frac{p_2}{rT_2}} \]

\[ w_{u2} = \frac{\pi D_{I2}}{60} n_T \]

\[ \tan \delta = \frac{w_{ref} \tan \gamma \pm w_u}{w_{ref}} \]

\[ q = h_{01} - h_{02} = K \frac{c_2^2 - w_2^2}{2} = \mp w_{ref}^2 \left( \tan^2 \gamma - \tan^2 \delta \right) \]

\[ w_{transf} = \frac{w_{ref}}{\cos \delta} \] (assessment of kin.en. dissipation)
3. Application of 1-D Modules to In-Turbine Flow Simulation

- Existing 1-D turbine model for steady flow: transformation into unsteady 1-D scheme

\[ q = h_{01} - h_{02} = \pm \frac{c_2^2 - w_2^2}{2} = \mp w_{ref}^2 \left( \tan^2 \gamma - \tan^2 \delta \right) \]
3. Application of 1-D Modules to In-Turbine Flow Simulation

Introduction

Tools for 1-D Simulation of a Radial Turbine

Application of 1-D Modules to In-Turbine Flow Simulation

Unsteady Flow Pipe P1

Flow Connection $\mu = 1$

Turbine Nozzle P2

Flow Connection

Stator Impeller P3

Flow Connection

Turbine Impeller RP 4

Flow Connection

Impeller - Stator P4

Unsteady Flow Pipe P1

half scroll length
3. Application of 1-D Modules to In-Turbine Flow Simulation

Amended modules

Sources and sinks of total enthalpy

\[ w_{ref} = \frac{m_1}{A_{ref} \frac{p_2}{rT_2}}; \quad w_{u2} = \frac{\pi D I_2}{60} n_T \]

\[ \tan \delta = \frac{w_{ref} \tan \gamma \pm w_u}{w_{ref}} \]

\[ q = h_{01} - h_{02} = K \frac{c_2^2 - w_2^2}{2} = +w_{ref}^2 \left( \tan^2 \gamma - \tan^2 \delta \right) \]

\[ w_{transf} = \frac{w_{ref}}{\cos \delta} \] (assessment of kin.en. dissipation)
3. Application of 1-D Modules to In-Turbine Flow Simulation

- Borda Carnot pressure recovery has to be compensated at transformation pipe connections (in a different way for subsonic and sonic regions).
- Amendment of rothalpy and centrifugal acceleration terms into energy and momentum conservation equations.

![Carnot/Borda Pressure "Loss" graph](image-url)
3. Application of 1-D Modules to In-Turbine Flow Simulation

Turbine torque has to be calculated from the change of angular momentum.

\[
\Delta M_{\text{T,turbine}} = \frac{\partial}{\partial t} \int_v r \times c \, \rho dV - \int_{\partial V} (r \times c) \cdot n \, \rho dA =
\]

\[
\frac{\partial}{\partial t} r \times c \, \rho \Delta V - \left[ m(r \times c) \right]_{\text{out}} + \left[ m(r \times c) \right]_{\text{in}} \approx \sum_i^{n} \left[ r \, m(\omega r + w \cos \varepsilon_i) \right]_{\text{in} i} + \left[ r \, m(\omega r + w \cos \varepsilon_i) \right]_{\text{out} i} - r(\omega r + w \cos \varepsilon_i) \left( m_{\text{in} i} - m_{\text{out} i} \right) + \left( m_j r_j^2 \frac{d\omega}{dt} - m_j r_j \cos \varepsilon_j \frac{dw_j}{dt} \right)
\]
3. Application of 1-D Modules to In-Turbine Flow Simulation

- **Leakage flows.**
- **Windage losses and mechanical efficiency prediction.**
- **Input of additional pressure losses (incidence angle, ...)** as the sink term of momentum and flow separation losses.
- **Backflows through impeller channels.**
- **Twin scroll flow mixing.**
- **Vaneless nozzle or downstream diffuser.**
4. Calibration of 1-D Turbine Model

To build GT Power model:

- Experiments at a turbine (reduced mass flow-rate & turbine efficiency at different PR and BSR \( u/c_s \))
- Geometrical parameters for GT Power model
- Calibration of GT Power model at steady flow using optimizer
- Use of GT Power model for unsteady simulations.
4. Calibration

- Calibration errors may be reduced:

  The experimental data subdivided into smaller groups in dependence on turbine speed.

  More flexible approach based on general optimization methods (e.g., genetic algorithms) finding generally valid fixed parameters.

Optimization results

- Total isentropic efficiency - low speed optimization

- Total discharge coefficient - Low speed optimization
4. Calibration of 1-D Turbine Model

- The first calibration procedure using “the best fit model parameters” using non-linear regression was published in SAE 2002-01-0337. It finds variable calibration parameters.

- More suitable approach is based on general optimization methods (e.g., genetic algorithms) finding generally valid fixed parameters.

- Calibration errors due to the variability of parameters may be reduced: The experimental data can be subdivided into smaller groups in dependence on turbine speed and/or pressure ratio.
5. Examples of Results

Examples of prediction of a turbine discharge coefficient and efficiency - steady flow.

The unsteady 1-D model has used only simplified losses yet, i.e., no look-up tables and no correction of incidence angle loss.
Introduction
Tools for 1-D Simulation of a Radial Turbine
Application of 1-D Modules to In-Turbine Flow Simulation
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Examples of

Velocity Map of a Radial Turbine

- data based on MS Excel Efficiency
- data based on 1-D GT-Power Efficiency
- Discharge Coefficient

Turbine map calculated from steady and 1-D unsteady models for the set of pressure and blade speed ratios.

Turbocharger test rig model used for steady flow tests.

Turbine used at 4 cylinder engine.

Isentropic Efficiency at Pressure Ratio=1
Isentropic Efficiency at Pressure Ratio=2.0
Isentropic Efficiency at Pressure Ratio=2.5
Isentropic Efficiency at Pressure Ratio=3.0
Isentropic Efficiency at Pressure Ratio=3.5

Discharge Coefficient at Pressure Ratio=2.0
Discharge Coefficient at Pressure Ratio=2.5
Discharge Coefficient at Pressure Ratio=3.0
Discharge Coefficient at Pressure Ratio=3.5

Efficiency data based on MS Excel
Efficiency data based on 1-D GT-Power
Discharge Coefficient
5. Examples of Results

Introduction

Tools for 1-D Simulation of a Radial Turbine

Application of 1-D Test at simulated turbocharger test-rig (turbine loaded by a compressor). Turbine operation close to optimum efficiency before sonic limit is reached.

Conclusion and Prospects
5. Examples of Results

Introduction
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Comparison of 0-D and 1-D Turbine Models at a 4 Cylinder, Single Exhaust Engine at 1200 rpm
5. Examples of Results

BSFC - Brake Specific Fuel Consumption, Part Engine

- 1-D_unsteady
- 0-D_GT-P_standard
- 0-D_GT-P_GridMap
- 0-D_regression
6. Conclusion and Prospects

- Steady model has been validated and prepared for expected application.
- The work on fully unsteady model in progress, application of detailed loss model will be done soon.
- Models under development:
  - **Twin scroll model** (momentum exchange, backflow to the other manifold branch, asymmetry of flows)
  - Impeller channel unsteadiness due to rotation along scroll. Use of unsteady channel-switching model from PWS (COMPREX®) SAE 2004-01-1000
Prospects

...an engine in... of “TPA” from GT
Conclusion and Prospects

Introduction to 1-D Simulation of a Radial Turbine

Application of 1-D Modules to In-Turbine Flow Simulation

Calibration of a 1-D Turbine Model

Future comprehensive model of a turbine: scroll/blades/impeller

Stator – Impeller

Stator – Impeller

Turbine Impeller RP 1

Turbine Impeller RP 2

Impeller – Stator P1

Impeller – Stator P2

Scroll Flow Split FS1

Scroll Flow Split FS2

Scroll Flow Split FS3

Turbine Nozzle N1

Impeller Leakage 1

Turbine Nozzle N2

Impeller Leakage 2

Stator Impeller P1

Stator Impeller P2

Turbine speed

Leakage

Impeller – Stator P2

Leakage

Conclusion and Prospects
A GT-POWER Based Predictive Radial Turbine Model

Thank you for your attention!

Questions?
Transformation StatorImpeller

Inputs (1...upstream, 2...downstream, 0 .. total)

\( \rho_1, p_1, T_1, h_{01}, p_{01}, T_{01}, c_{p1}, \kappa = \frac{c_p}{c_v}, A_1, \ldots, \)

\( p_2, A_{2\text{ref}}, \gamma \) (angle of blades, actuated)

\( C_p = \frac{1}{\eta} - 1 \) (isentropic efficiency of \( \Delta h \rightarrow \frac{w^2}{2} \), actuated)

\( C_D = K_{\text{sep}} \) (coefficient of flow contraction in Flow Connection, actuated)

\( K = \begin{cases} -1 & \text{stator} \rightarrow \text{imp} \\ +1 & \text{imp} \rightarrow \text{stator} \end{cases} \)
Transformation StatorImpeller

Velocity and total state transformation

\[
\begin{align*}
\dot{w}_\text{ref} &= \frac{m_I}{A_{\text{ref}} \frac{p_2}{r T_2}}; \quad \dot{w}_u = \frac{\pi D_{I2}^2}{60} n_T \\
\tan \delta &= \frac{w_{\text{ref}} \tan \gamma + Kw_u}{w_{\text{ref}}} \\
T_{02} &= T_{01} + K \frac{w_{\text{ref}}^2}{2c_p} \left( \tan^2 \gamma - \tan^2 \delta \right) \\
h_{02} &= h_{01} + Kw_{\text{ref}}^2 \left( \tan^2 \gamma - \tan^2 \delta \right) \\
W_{\text{transf}} &= \frac{w_{\text{ref}}}{\cos \delta} \quad (\text{assessment of kin.en. dissipation})
\end{align*}
\]
Transformation StatorImpeller

Outputs

\[ m, \rho_2, h_{02}, W_2, w_{\text{ref}}, w_{\text{transf}}, T_{02}, \delta \] (angle of flow)