A MARINE TURBOCHARGER COMPRESSOR MULTI-POINT 3D DESIGN OPTIMIZATION TOOL

K. Ntonas, N. Aretakis, K. Mathioudakis

Laboratory of Thermal Turbomachines, School of Mechanical Engineering
National Technical University of Athens, Greece

ASME Turbo Expo 2021
June 7 – 11

Marine turbocharger compressor multi-point 3D design optimization tool

A marine turbocharger 3D compressor design tool is presented. It produces 3D centrifugal compressor geometry for optimal compressor retrofit. It encompasses two modules, allowing the design process to become fully automatic.

- **1D compressor multi-point design optimization process, aiming to provide a fast and reliable solution based on Turbocharged diesel Engine range of operation.**
- **3D compressor multi-point design optimization process, producing optimized 3D compressor geometry.**

The tool is implemented on an existing marine turbocharger retrofit platform[1]

(1) Ntonas, K., Aretakis, N. , Roumeliotis, I. and Mathioudakis, K., "A Marine Turbocharger Retrofitting Platform," ASME Journal of Engineering for Gas Turbines and Power, 142 (11) Article No. GTP-20-1402/111008.(2020) (Also *Proceedings of ASME Turbo Expo*. GT2020-14643. Virtual, Online, September 21-25, 2020).

Contents

Contents

Methodology

1. Turbocharger compressor multi-point design tool
2. Turbocharger compressor 1D design tool
3. Simplified Structural Analysis
4. 1D Compressor model validation
5. Turbocharger compressor 3D design tool

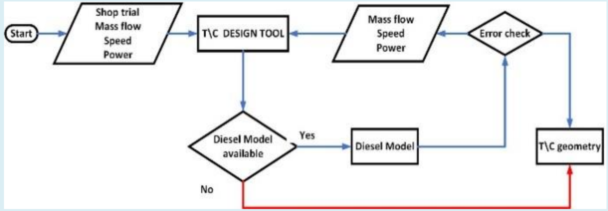
Application test case

1. Test case specifications
2. Turbocharger compressor 1D design analysis
3. Turbocharger compressor 1D design 3D geometry analysis
4. Evaluation of Modified 1D module
5. 3D compressor design

Summary & Conclusions

Turbocharger compressor multi-point design tool

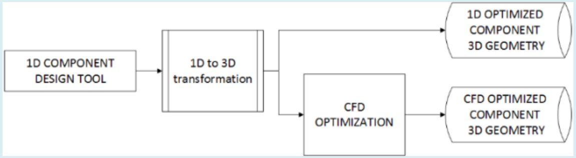
- **The design tool focuses on a multi-point T\C operation, with the capability of being adjusted to retrofitting requirements.**
  - ✓ CC design.
  - ✓ Turbine design.
  - ✓ Entire T\C design.
- **Single zone thermodynamic combustion model for the closed diesel engine cycle[1]. (Validation case in (1))**
- **1D centrifugal compressor model based on methodology presented by Aungier [2]. (Validation case in present study)**
- **1D radial turbine model based on methodology presented by Wasserbauer [3] . (Validation case in (1))**
- **Both CFD compressor and Turbine models: ANSYS CFX**



(1) Ntonas, K. Aretakis, N., Roumeliotis, I., Pariotis, E., Paraskevopoulos, Y. and Zannis T., "Integrated Simulation Framework for Assessing Turbocharger Fault Effects on Diesel Engine Performance and Operability." ASCE Journal of Energy Engineering, 146 (4) Article No. 04020023.(2020).
(2) Aungier, R.H., "Centrifugal Compressors," ASME PRESS, 2000 .
(3) Wasserbauer, C.A. and Glassman, A. J., "Fortran Program for predicting off-design performance of Radial-Inflow Turbines." Technical Report No. TN D-8063. NASA Lewis Research Center, Cleveland, Ohio. 1975.

Turbocharger compressor multi-point design tool

- **T/C design tool consists of two component sub-tools.**
  - ✓ Compressor
  - ✓ Turbine



- **Each design sub tool utilizes 1D and CFD models.**
- **Sub-tool utilities**
  - ✓ Fast and reliable preliminary design option(1D Module).
  - ✓ High fidelity design option(3D Module).
- **Objective function in case of available Diesel Engine**

$$min: z = \frac{\sum hr_i W_{f,i}}{\sum hr_i}$$

- **Objective function in case of no available Diesel Engine**

$$max: z' = \frac{\sum hr_i \eta_i}{\sum hr_i}$$

- **The present study focuses only on compressor design (original turbine is retained).**

Turbocharger compressor multi-point design tool

The optimization constrains are appropriately chosen in order to make the new compressor manufacturable and operable.

- **Structural integrity: Compressor maximum tensile stress at the highest compressor speed operating point must not exceed the yield point by a given safety factor.**
  - ✓ 1D module: Usage of simplified structural analysis.
  - ✓ 3D module: Usage of ANSYS Static Structure
- **Compressor must operate in stable region with an acceptable surge margin.**
- **Blade thickness must be greater than a given minimum CNC machine value.**
- **Volute pressure recovery must be greater than 0.21 according to Ceyrowsky et. al.[(1)] (for 1D Module only).**

(1) Ceyrowsky, T., A. Hildebrandt & Schwarze, R., "Numerical investigation of the circumferential pressure distortion induced by a centrifugal compressor's external volute," *Proceeding of ASME Turbo Expo*, GT 2018-75919 Oslo, Norway, 2018.

Turbocharger compressor 1D design tool

In 1D module, a 1D optimization procedure is followed, redesigning the compressor in order to match the entire system in an optimum way, retaining the original turbine.

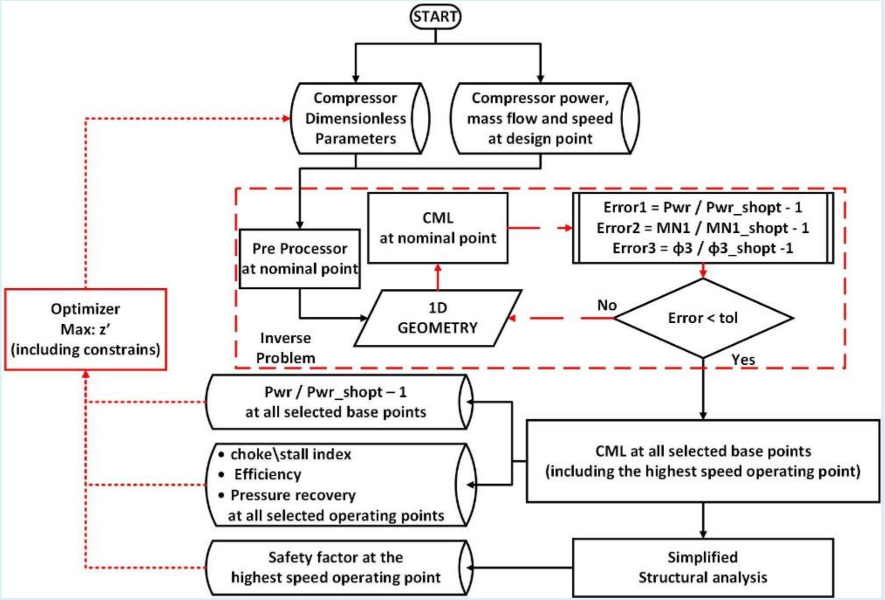
- **Usage of dimensionless parameters for a optimization process, fully automatic.**
- **Constant variables ranges are imposed.**
- **Random initial geometry.**
- **Adaptive simulated annealing (ASA).**

Parameter	Range	Parameter	Range
$\beta_{b,1}$	(0,90°)	B_3	(0,0.3)
$\beta_{b,3}$	(0,70)	AR_{vnl}	>1.15
MN_1	(0.1,0.9)	AR_{vol}	>0
φ_3	(0.1,0.5)	Z	(6,40)
B_1	(0,0.3)	$R_{hub,1}/R_{tip,1}$	(0.25,0.70)

Turbocharger compressor 1D design tool

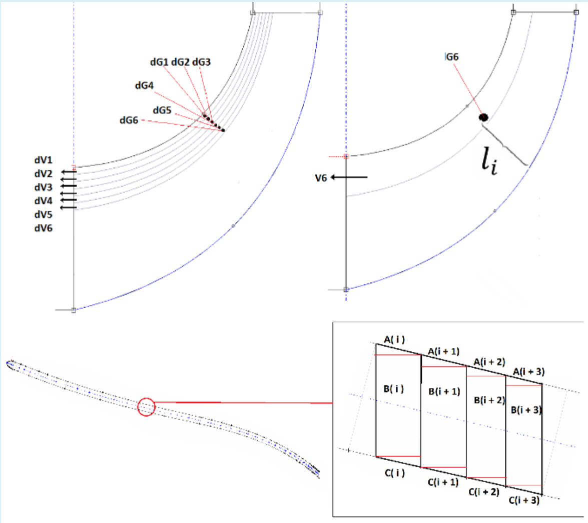
The usage of dimensionless parameters is achieved by coupling a typical compressor 1D mean line model with a pre-processor, capable of transforming dimenionless parameters into 1D geometry.

- **Preprocessor input data:** Pwr_{cmp}, $\dot{m}$, Z, N, $\beta_{b,1}$, $\beta_{b,3}$, MN_1, ϕ_3, B_1, B_3, AR_{vnl}, AR_{vol}, Cl_{ratio}
- **Preprocessor output data:** $D_{hub,1}$, $D_{tip,1}$, $\beta_{b,1}$, D_3, D_4, D_5, $\beta_{b,3}$, t_1, t_2, N, Cl, Z, l_{cmp}
- **Clearance ratio : typical value (0.008).**
- **One operating point is chosen as nominal point and the rest of them as base points.**
- **Power and mass flow can be found in shop trials data.**



Simplified Structural Analysis

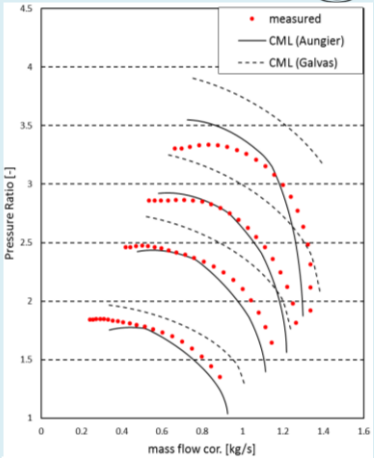
- **Two impeller stresses analysis.**
  - ✓ Tensile stresses.
    - Centrifugal Force
  - ✓ Blade bending stresses.
    - Centrifugal Force
    - Pressure distribution

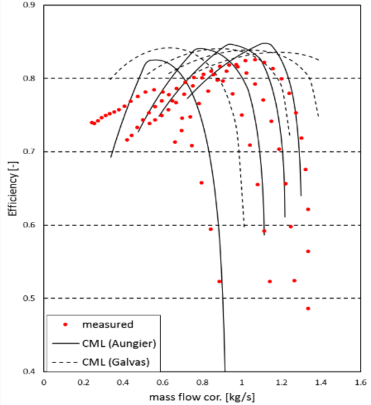


- **Impeller inertia and mass calculation.**
  - ✓ Usage of 1D to 3D geometry transformation.
  - ✓ Discretizing the volume in small sub volumes.
  - ✓ Each volume: divided into a number of sufficient parallelogram elementary elements.
  - ✓ Each element: splitted into two triangular elements and one rectangular.

1D Compressor model validation

- **Compressor meanline model validation.**
  - ✓ Specific commercial centrifugal compressor, provided by T/C manufacturer partner company.
  - ✓ Comparison with older meanline model [1]
- **Simplified Structure Analysis.**
  - ✓ Usage of test case optimized compressor geometry .
  - ✓ Validation using ANSYS Structure analysis.
  - ✓ ANSYS Static Structural: 347 Mpa.
  - ✓ Simplified static structure: 399 MPa.

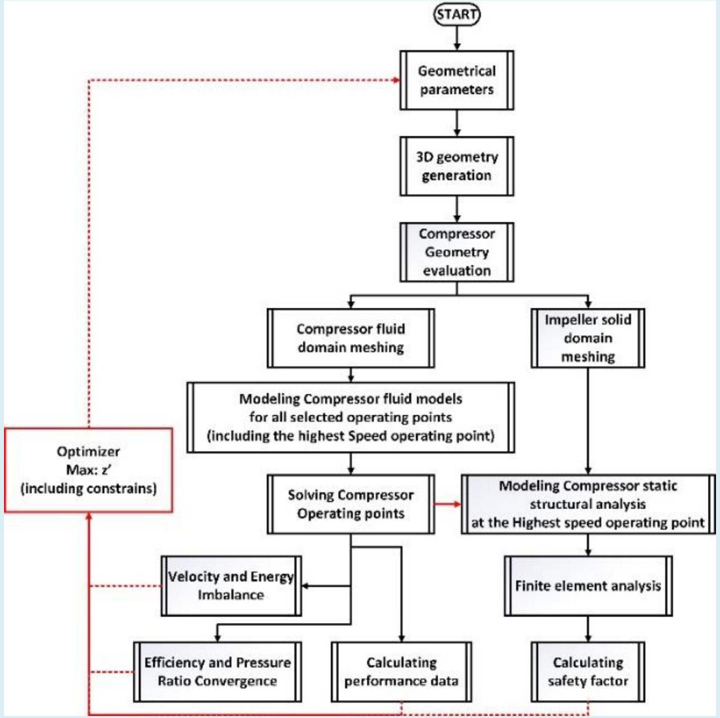




(1) Galvas, M.R., "Fortran program For predicting off design performance of Centrifugal Compressor," NASA TN D-7487, Lewis Research Center, Cleveland, Ohio 44135, 1973.

Turbocharger compressor 3D design tool

An in-house utility function is developed, with the aim to run specific ANSYS processes in the background, such as fluid domain meshing and fluid domain modeling, in order to automate the compressor CFD performance prediction.



- **Impeller Group A:** Z, $R_{hub,1}$, $R_{hub,a}$, $R_{hub,3}$, R_4, $R_{tip,1}$, $R_{tip,a}$, $R_{tip,3}$, $X_{hub,a}$, $X_{hub,3}$, $X_{tip,a}$, $X_{tip,3}$
- **Impeller Group B:** $\beta_{hub,1}$, $\beta_{hub,b}$, $\beta_{hub,3}$, $\beta_{tip,1}$, $\beta_{tip,a}$, $\beta_{tip,b}$, $\beta_{tip,3}$, $t_{hub,}$, $t_{hub,}$, $t_{hub,3}$, $t_{tip,1}$, $t_{tip,a}$, $t_{tip,3}$
- **Volute Variables(Semi external Volute):**
  - ✓ Inlet radius.
  - ✓ Outlet radius
  - ✓ Elliptical parameter across circumferential direction.

Turbocharger compressor 3D design tool

- **Evolutionary algorithm optimization method.**
- **1D Module 3D geometry as initial geometry.**
- **CFD setup:**
  - ✓ Advection scheme: Upwind.
  - ✓ Turbulence model: SST (5% Intensity)
  - ✓ Max y+ value 2.58
    - Impeller mesh size: 2 millions
    - Volute mesh size: 150000

- **CFD convergence criteria:**
  - ✓ Velocity and Energy RMS residuals <=10-5.
  - ✓ Velocity and Energy imbalance <0.1% (Used to ensure that compressor is operates stably).
  - ✓ Outlet pressure ratio and efficiency deviation from average ones, calculated from the past 50 iterations, lower than a tolerance value.

Contents

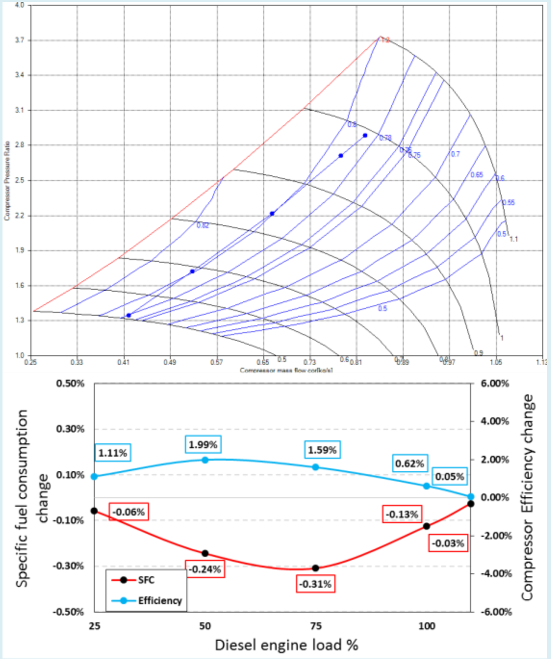
Application test case

- A 5-cylinder 4-stroke diesel generator T/C compressor is to be redesigned
- Diesel Engine model is calibrated
- Shop trials are available
- Turbine is retained
- Impeller material: Typical Aluminum Alloy.
- Nominal point: 75% Engine Load
- Base Point: 50% Engine Load
- Highest speed operating point: 110% Engine Load

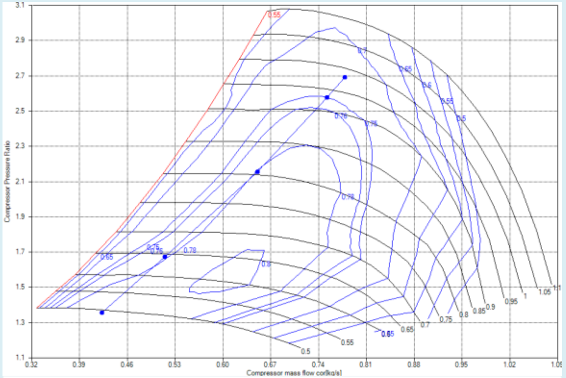
- Objective function:
  - $max: z' = 0.5\ \eta_{cmp,50} + 0.5\ \eta_{cmp,75}$
- Modification of Compressor 1D model:
  - ✓ Overcoming the Meanline model inability to capture:
    - Impact of impeller outlet blade length in recirculation and active flow region generation
    - Volute losses due to 3D effects
  - ✓ $A_3/A_1 = -1.51\ \Phi + 1.0137$
  - ✓ Φ: flow coefficient
  - ✓ A_3/A_1: impeller outlet to inlet area ratio

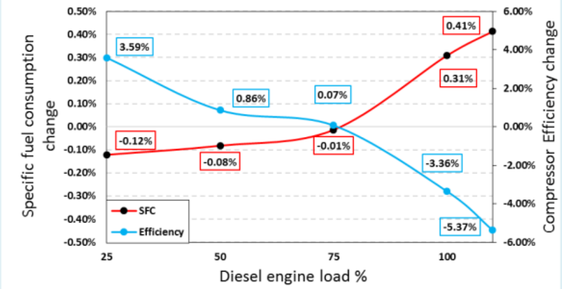
Turbocharger compressor 1D design analysis

- **Compressor Efficiency:**
  - ✓ Engine Load 50%: 1.99% increase.
  - ✓ Engine Load 75%: 1.59% increase.
- **Specific fuel consumption:**
  - ✓ Engine Load 50%: 0.24% decrease.
  - ✓ Engine Load 75%: 0.31% decrease.
- **For higher SFC decrease Turbine geometry must be included in design process (Original Turbine operation is moved to lower efficiency areas).**
- **Impeller safety factor: 1.25.**



Turbocharger compressor 1D design 3D geometry analysis



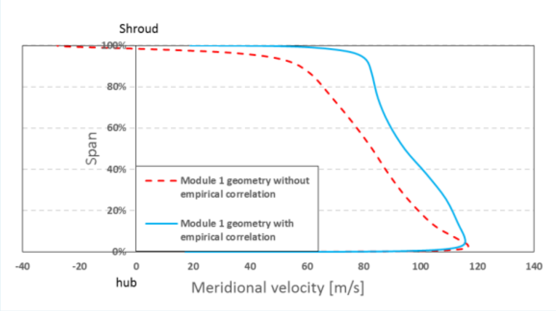


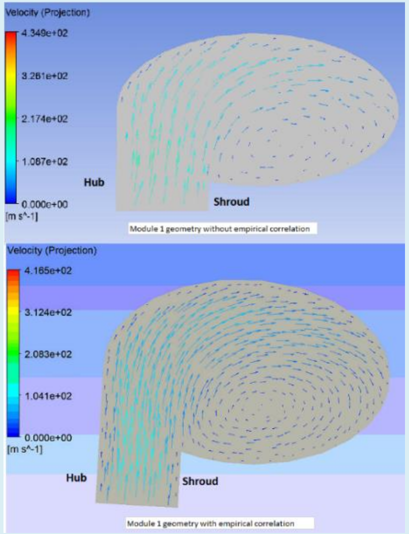
- **Compressor Efficiency:**
  - ✓ Engine Load 50%: 0.86% increase.
  - ✓ Engine Load 75%: 0.07% increase.
- **Specific fuel consumption:**
  - ✓ Engine Load 50%: 0.08% decrease.
  - ✓ Engine Load 75%: 0.01% decrease.
- **Impeller safety factor: 1.44.**
- **1D module:**
  - ✓ Provides a 3D compressor geometry which reconstitutes (slightly improve) the original compressor performance.
  - ✓ A low time consuming process with very low computational resources requirements.
  - ✓ Provides an Initial geometry for the 3D module.

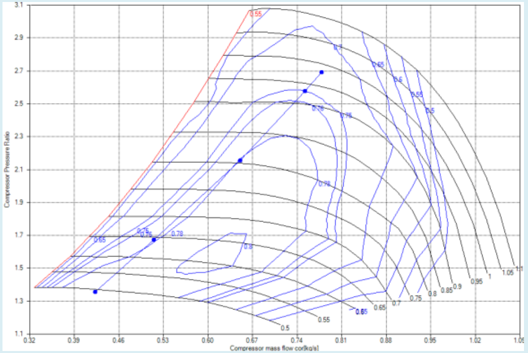
Evaluation of Modified 1D module

Comparison between 1D module 3D geometries with and without the Modification of Compressor 1D model shows that the empirical correlation provides a compressor with.

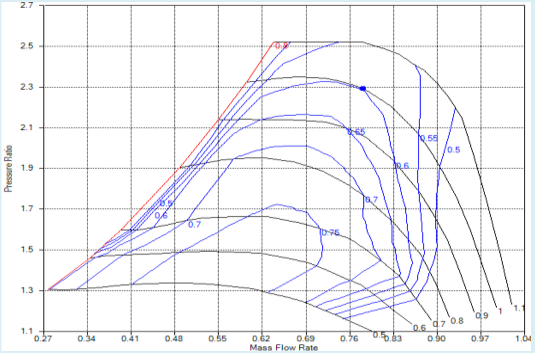
- **Outlet blade height reduction (27.3%).**
- **Outlet flow recirculation area reduction.**
- **Volute lower 3D effects.**







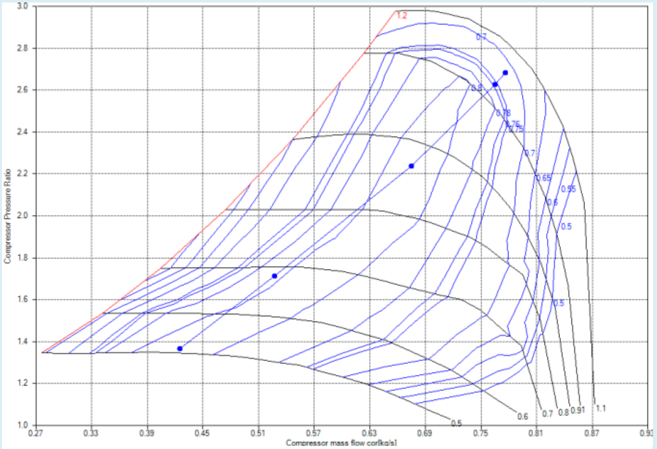
With correlation

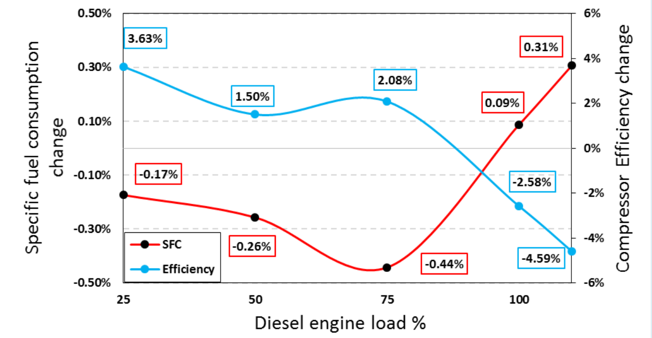


Without correlation

3D compressor design

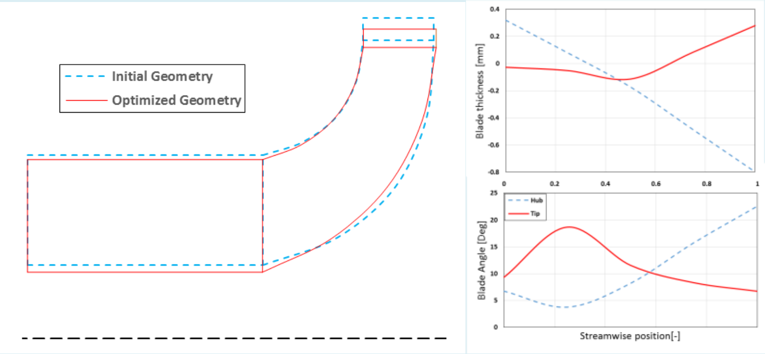
- 1D module 3D geometry usage as initial geometry.
- Compressor Efficiency:
  - ✓ Engine Load 50%: 1.50% increase.
  - ✓ Engine Load 75%: 2.08% increase.
- Specific fuel consumption:
  - ✓ Engine Load 50%: 0.26% decrease.
  - ✓ Engine Load 75%: 0.44% decrease.
- Impeller safety factor: 1.35.





3D compressor design

- Variation in blade shape.
- Small variation in meridional geometry
- The meridional geometrical parameters can be skipped reducing the computational time.
- 2.23% reduction for volute outlet radius from rotational axis.
- 2.93% increase for volute outlet radius.
- Both optimized compressor geometries, generated by 1D and 3D module, have a size close to the baseline one.

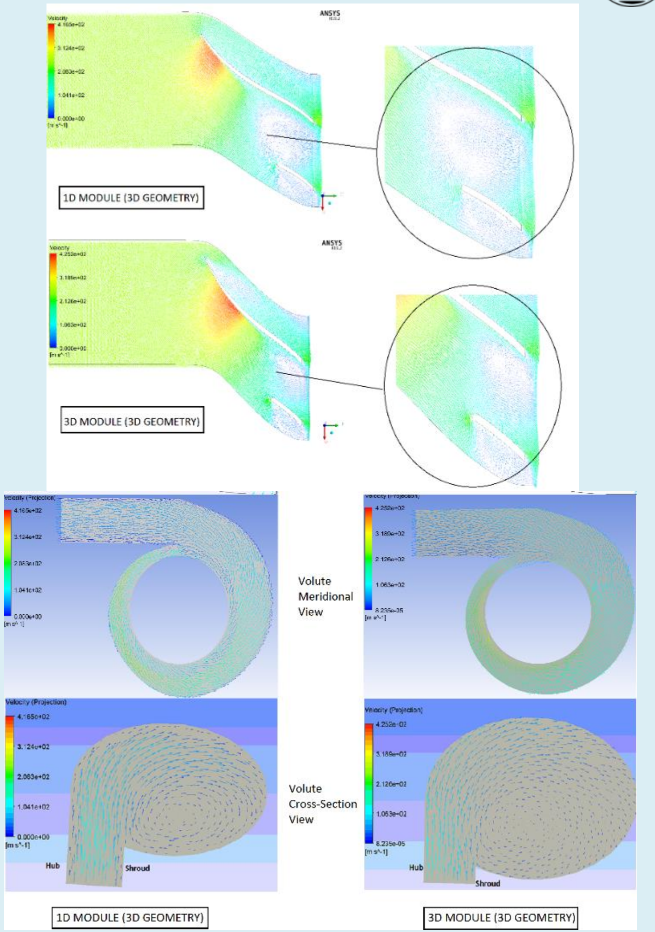


Parameter	1D module	3D module
$R_{hub,1}$	10.1%	0.5%
$R_{tip,1}$	-17.5%	-20.4%
R_3	-4.2%	-6.8%
R_4	1.2%	-2.3%
R_5	-3.9%	-1.6%
R_{vol}	-9.5%	-12.7%
$\beta_{hub,1}$	-65.6%	-25.1%
$\beta_{tip,1}$	31.4%	40.5%
β_3	-12.9%	22.3%
b3	24.2%	33.2%
Main Blades	-1	-1
Splitter Blades	-1	-1

3D compressor design

Concerning efficiency increase resulting from CFD optimization.

- **Impeller flow close to shroud enhancement.**
  - ✓ Wake flow region reduction.
  - ✓ Impeller flow loss reduction.
- **Volute flow enhancement**
  - ✓ Smoother flow into the volute component.
  - ✓ Volute losses due to 3D effects reduction.



Contents

Summary & Conclusions

- A marine turbocharger multi-point 3D compressor design tool is presented. It is implemented on an existing retrofit platform and utilizes 1D and 3D CFD design tools. It uses an optimization process, in order to provide an improved retrofitting solution, aiming to at least reconstituting the original diesel engine performance.

- Taking advantage from the usage of dimensionless parameters as optimization variables with defined range, it can provide a robust, fast converging and fully automatic procedure using shop trials data as the only inputs, hence not requiring the original compressor geometry and performance.

- The first module (1D design) in combination with the 1D to 3D transformation tool and a simplified structure model provides a fast operable and manufacturable compressor 3D geometry.

- In second module (3D design), another optimization procedure is performed using CFD and FEA analysis. Taking advantage from the first module results, the 3D design module does not rely on an initial 3D geometry, which in many cases is not available.

Summary & Conclusions

- The tool is applied to a real retrofitting case study where a T/C compressor needs to be redesigned.
  - **Using the 1D module.**
    - ✓ 2% maximum compressor efficiency increase compared to baseline.
  - **CFD analysis using 1D module 3D geometry.**
    - ✓ 1D module 3D compressor operates more efficiently compared to baseline.
    - ✓ Reliable tool for fast compressor 3D design.
  - **CFD analysis: using 3D module 3D geometry.**
    - ✓ Up to 2% maximum compressor efficiency compared to baseline increase.
  - **Comparison between 1D module and 3D module 3D geometries.**
    - ✓ Small variation in meridional geometry.
    - ✓ The user can disable impeller meridional geometrical optimization variables (computational time reduction).

A MARINE TURBOCHARGER COMPRESSOR MULTI-POINT 3D DESIGN OPTIMIZATION TOOL

Thank you very much for your attention