USE OF BLADE LEAN IN TURBOMACHINERY REDESIGN

John Moore, Joan G. Moore, and Alex Lupi

Mechanical Engineering Department
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061-0238

Blade lean is used to improve the uniformity of exit flow distributions from turbomachinery blading. In turbines, it has been used to control secondary flows by tailoring blade turning to reduce flow overturning and underturning and to create more uniform loss distributions from hub to shroud.

In the present study, the Pump Consortium centrifugal impeller has been redesigned using blade lean. The flow at the exit of the baseline impeller had large blade-to-blade variations, creating a highly unsteady flow for the downstream diffuser. Blade lean is used to redesign the flow to move the high loss fluid from the suction side to the hub, significantly reducing blade-to-blade variations at the exit.

Axial Flow Turbine Stators
Consortium Pump Impeller Problem
Secondary Flow Analysis for a Rotor
Stable Location of High Loss Fluid
Impeller Redesign
Improved Performance

Use of Blade Lean in Axial Flow Turbine Stators
VP in Cross-Sections
Controlling Exit Loss Distributions
Linear Cascade

No Lean
Static pressure contours established by primary flow.

Blade Lean
Boundary layer flow towards top endwall/suction side corner region.

Compound Lean
Boundary layer accumulation towards midspan.

Annular Cascade

No Lean
Expect more losses in hub/suction side corner region.

Tangential Lean
Opposing radially inward flow in suction side boundary layer.

Compound Lean
Spreading loss spanwise.
Effect of tangential lean on stator vane losses
Effect of compound lean on stator vane losses
Total pressure loss contours:
Phase II stator

Total pressure loss contours:
Phase I/
Model D stator
CONSORTIUM IMPELLER BASELINE DESIGN
Consortium Impeller, Baseline Design
Exit Plane Distortion

\[ V_{\theta}, \theta \]

\[ V^2 \alpha, \theta \]
Equations for Incompressible Flow in a Rotating System

Reduced static pressure

\[ p_r = p - \frac{1}{2} \rho \omega^2 r^2. \]

Rotary stagnation pressure

\[ p^* = p + \frac{1}{2} \rho \Omega^2 - \frac{1}{2} \rho \omega^2 r^2 \]

Absolute vorticity

\[ \Omega = \nabla \times \mathbf{V} = \nabla \times \mathbf{W} + 2\Omega \]

Momentum, inviscid flow

\( (\mathbf{W} \cdot \nabla) \mathbf{W} + 2\Omega \times \mathbf{W} = -\frac{1}{\rho} \nabla p_r \)
Determining the Stable Orientation Vector for Secondary Vorticity Suppression in Rotating Systems

Secondary Circulation, Hawthorne

\[
\frac{\partial}{\partial s} \left( \frac{\Omega_s}{W} \right) = \frac{2}{\rho W^2} \left( \frac{1}{R_n} \frac{\partial p^*}{\partial b} + \frac{\omega}{W} \frac{\partial p^*}{\partial z} \right)
\]

From momentum

\[
W \times \Omega = \frac{1}{\rho} \nabla p^*
\]

or

\[
W \cdot \nabla p^* = 0, \quad \nabla p^* \perp W
\]

Generation of secondary circulation = 0 when

\[
W \cdot \left( \left[ \frac{-1}{\rho} \nabla p_t - \omega \times W \right] \times \nabla p^* \right) = 0
\]

I.e. the component of the vector

\[
\frac{-1}{\rho} \nabla p_t - \omega \times W
\]

perpendicular to the relative velocity points to the stable location of high loss fluid.
Consortium Impeller, Baseline Design

Stable location vectors

Contours of Pr and P*
Consortium Impeller

Stable location vectors

Contours of Pr

Baseline design

Design: lean A
CONSORTIUM IMPELLER

REDESIGN: LEAN A
Consortium Impeller
Design: lean A
Contours of $P^*$
Consortium Impeller

Contours of P at the impeller exit

Baseline design

Design: lean A
Consortium Impeller, Design: Lean A
Exit Plane Distortion

\[ \theta \]

\[ \alpha \]

\[ V^2 \]

\[ \theta \]

\[ \theta \]

\[ V^2 \alpha \]

\[ \theta \]

\[ \theta \]
Circumferential Averages

Baseline

\[ \delta P_t = 1.22 \quad \eta = 98\% \]

\[ \eta \]

\[ V_\theta \]

\[ p^* \]

Lean A

\[ \delta P_t = 1.24 \quad \eta = 98\% \]

\[ \eta \]

\[ V_\theta \]

\[ p^* \]
CONCLUSIONS

Consortium Pump Impeller

Redesigned using Blade Lean

Improved tangential uniformity of exit flow distribution

Reduced diffuser vane excitation forces