A DESIGN OPTIMIZATION STRATEGY FOR OPEN-CHANNEL FLOWS USING DISCRETE SENSITIVITY ANALYSIS

By

Clarence Oscar Edwin Burg

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Name: Clarence Oscar Edwin Burg

Date of Degree: August 6, 1999

Institution: Mississippi State University

Major Field: Computational Engineering

Major Professor: Dr. David H. Huddleston

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Candidate for Degree of Doctor of Philosophy

A computationally efficient, gradient-based design optimization methodology is applied to high-velocity open-channel flow via an existing two-dimensional, finite element open-channel simulation code. For a given open-channel design, the flow through the channel is numerically approximated using the flow solver. Using the steady-state flow variables, the quality of the open-channel design is determined by a nonlinear least-squares objective function that measures the non-uniformity of the flow depths for a region within the channel. The gradient of this objective function with respect to the design variables is estimated accurately and efficiently via discrete sensitivity analysis, removing the computational cost of multiple steady-state simulations per design iteration. The gradient information is used via a modified Gauss-Newton optimization algorithm to update the design variables to achieve rapid convergence to an optimal design. To demonstrate its robustness and computational efficiency, this design optimization strategy is applied without any modifications to the design of channel contractions, expansions, bends and embedded bodies.

DEDICATION

To the glory of God the Father, God the Son and God the Holy Spirit, who made a beautiful world and filled it with order and organization and who has given mankind the ability and desire to understand His creation.

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NOMENCLATURE

F	Objective Function
$f_k, f_{i,j}$	Residual Functions in Gauss-Newton Algorithm
$\vec{\beta}$	Vector of Design Variables
β_i	ith Design Variable
$\vec{\beta}^n$	Design Variables for nth Design Iteration
$\frac{\partial F}{\partial \beta_i}$	Design Space Derivative
$\nabla_{\vec{\beta}} F$	Design Space Gradient
$\frac{dF}{d\beta_i}$	Total Variation of F with respect to β_i
$\vec{Q}$	Flow Variables
$\vec{Q}^{n+1}, \vec{Q}^n, \vec{Q}^{n-1}$	Time-Dependent Flow Variables
$\vec{Q}^{n,m}$	Flow Variables for Newton-Raphson Iterations
e_i	A zero vector with 1 in the ith entry
$\Delta x, \Delta \beta$	Perturbation Amount
χ	Computational Domain for Flow Variables
Ω_a, Ω_F	Computational Domain for Objective Function
W	Residual Vector Resulting from Discretized Equations
$W_{i,1}, W_{i,2}, W_{i,3}$	Integral Equations Associated with Node i
$\frac{\partial W}{\partial Q}$	Jacobian of Residual Vector with respect to Flow Variables

$\frac{\partial Q}{\partial \beta_i}$	Change in the Flow Variables with respect to the Design Variable
λ, λ_j	Adjoint Vector, Adjoint Variables
$\mathcal{L}$	Lagrangian for Continuous Sensitivity Analysis
$\delta\mathcal{L}$	Variation in Lagrangian
h	Depth of Flow
h_{ave}	Average Depth over Domain Ω_F
h_k^{target}	Target Depths for Inverse Problem
u, v	X-Velocity, Y-Velocity
$p = hu, q = hv$	X-Discharge, Y-Discharge
$\sigma_{xx}, \sigma_{xy}, \sigma_{yx}, \sigma_{yy}$	Reynolds Stresses
g	Gravity
n	Manning's Friction Coefficient
z	Bed Elevation
C_o	Dimensional Constant
P	Pressure
ρ	Density of Water
W_L	Spatially First-Order Residual Vector
W_H	Spatially Higher-Order Residual Vector
$\vec{p}^n$	Search Direction at Iteration n
Δx	Step Size at Iteration n
B_n, B_{n+1}	Approximate Hessian Matrices for BFGS Update Method

r_i	Residual Function for Gauss-Newton Method
ν	Levenberg-Marquardt Constant
λ_{min}	Distance to Minimum of Quadratic Approximating Function
S_o, S_f	Bed Slope and Frictional Slope
b	Width of Channel
ν_t	Kinematic Viscosity
ψ_i	Weight Function for Finite Element Method
ϕ_i	Galerkin Weight Function
φ_i	Petrov-Galerkin Weight Function