Problem Formulation Report – RIYA Program 2023

FLOW PARAMETERS CALCULATION OF HYDRAULIC BUSHINGS

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Introduction

Motivation:

- Bushings are suspension devices used for vibration control, noise reduction, and improved ride quality. For optimum performance high damping and stiffness is needed for large-amplitude, low-frequency excitations, and low values at high frequencies to isolate noise. [1]
- Hydraulic bushings meet such requirements but exhibit highly non-linear & loading dependent physics that isn't fully understood. [2]
- The loading on a hydraulic bushing can comprise of – 1) A static mean load + 2) Dynamic displacement excitations which can be sinusoidal, step-like, etc., & can result in complex highly non-linear responses.

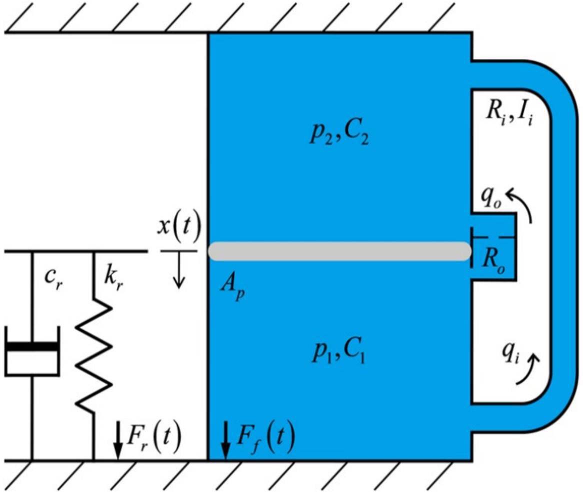

Figure 1. *Lumped Parameter model of a Hydraulic bushing* [2]

Goal:

- Investigate physics of dynamic flow characterization experiment, described in NOISE-CON 2023 paper [3]
- Evaluation of bushing's inertia track parameters under different flow conditions
- Computation of dynamic properties of leakage path in hydraulic bushings

Literature Review

Paper	Takeaways
Nonlinear fluid damping models for hydraulic bushing under sinusoidal or transient excitation [2]	• Flow conditions aren't restricted to one regime • Quasi-Linear models unable to capture transient response • Incorporating transitional flow resistance improves accuracy • Non-linearities arising from inertia track are more dominant than leakage path
Experimental dynamic flow characterization of hydraulic bushings [3]	• Flow characteristics of bushings is more complex than orifices • The flow characteristics depend on the nature of flow in the channels of bushings • Dynamic responses are highly non-linear & less consistent
Time domain responses of hydraulic bushing with two flow passages [4]	• Linear model yields good prediction for harmonic, low-amplitude excitations when a single long track is present • Effective damping is highly dependent on excitation amplitude for step-like inputs • Damping properties of bushings are enhanced on inclusion of short-passages

Problem Formulation

Objective 1a: Simulation of dynamic flow characterization experiment of NOISE-CON 2023 paper. [3]

Objective 1b: Polynomial approximation of pressure drop due to fluid resistance.

Objective 1c: Identification of flow nature & calculation of inertance, resistance for experimental data.

Objective 2: Investigate the physics of flow when a leakage path is also present.

Scope & Assumptions:

a) Bushing elements are to be analyzed one-by-one.

b) Compliance of system not taken into account.

c) Bushing fluid is incompressible and viscous in nature.

d) Only inertia track is present (Disregarded in Objective-2).

Objective 1a

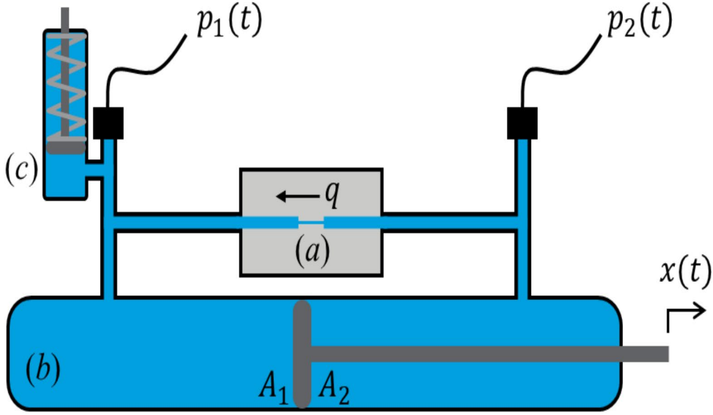

Figure 2: *Flow characterization experiment setup* [3]

Simulation of dynamic flow characterization experiment:

- Control Volume: Bushing domain between the two pressure transducers $p_1(t)$ & $p_2(t)$.
- Input: Sinusoid flow, $q(t) = q_m\, sin(2\pi f t)$, f - Excitation frequency.
- Pressure drop, Δp, in the bushing's inertia track happens due to fluid resistance & inertance.

- Resistance (R):
  - $\Delta p_R(t) = R(t)q(t)$.
  - Laminar, $R(t) = R_L$.
  - Turbulent, $R(t) = R_T = k_T q(t)^{0.75}$.
  - Orifice, $R(t) = R_O = k_O q(t)$.

- Inertance (I):
  - $\Delta p_I(t) = I \frac{dq(t)}{dt}$.
  - Linear formulation, $I = k_I \frac{\rho l}{A}$.

- Here, k_T, k_O, k_I are proportionality constants for turbulent resistance, orifice resistance & inertance, respectively. Their values depend on track geometry & fluid properties. [5]
- Total Pressure drop, $\Delta p(t) = \Delta p_I(t) + \Delta p_R(t)$.

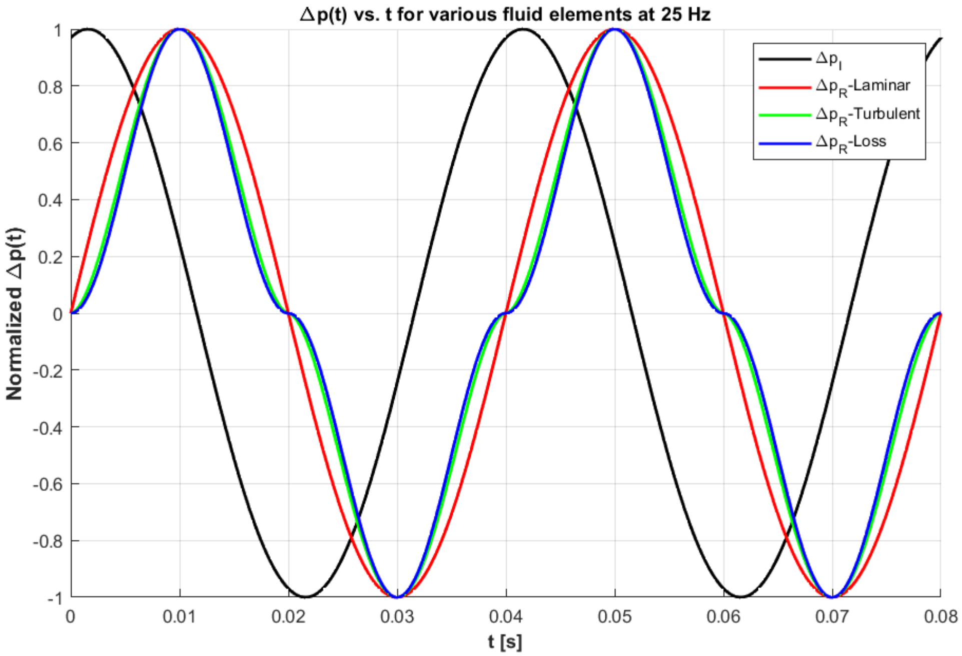

Figure 3a: *$\Delta p(t)$ profile for different fluid elements at excitation frequency of 25 Hz.*

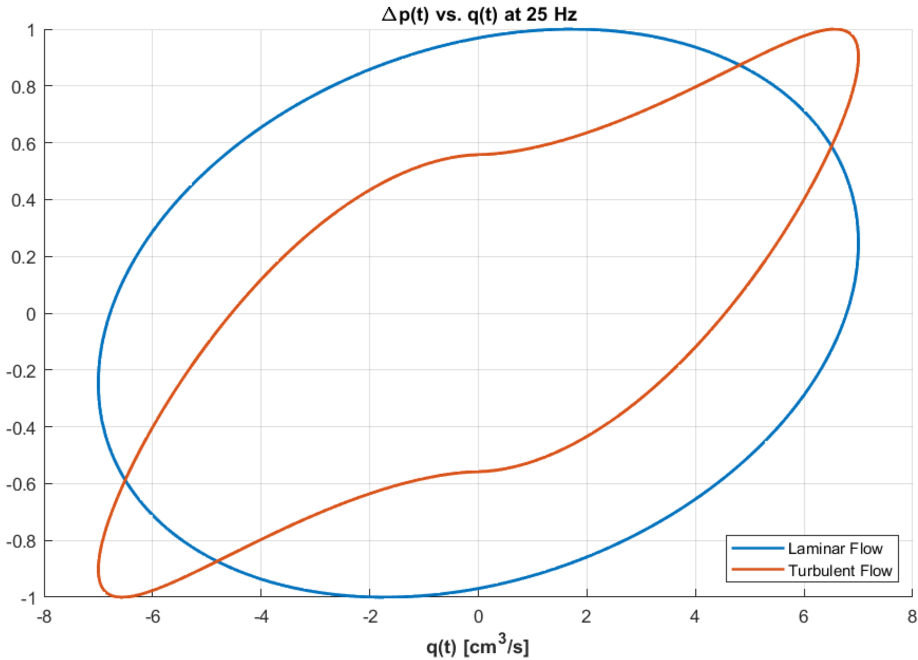

Figure 3b: *Plot for $\Delta p\ vs.q$ curve under laminar & turbulent flow conditions.*

- 90° phase difference between inertia & resistive effects can be used to calculate approximate value of inertance.
- Difference in pressure profile under different flow conditions can be seen from Fig. 3a.
- Fig. 3b highlights the difference of shape in $\Delta p\ vs.q$ curve between laminar & turbulent flow.

Objective 1b

Polynomial approximation of pressure drop due to fluid resistance:

- Turbulent Flow = $\Delta p_R \sim q^{1.75}$, Flow through orifice-like element = $\Delta p_R \sim q^2$.
- Requirement - Approximate Δp_R as a polynomial of flow rate, q → $\Delta p_R = \Delta p_R(q)$.

a) Taylor's Expansion at some operating point, q_{op}-

- Solution converges for $q \in [0, 2q_{op}]$.

b) Polynomial Fit -

- Using least-squares method.

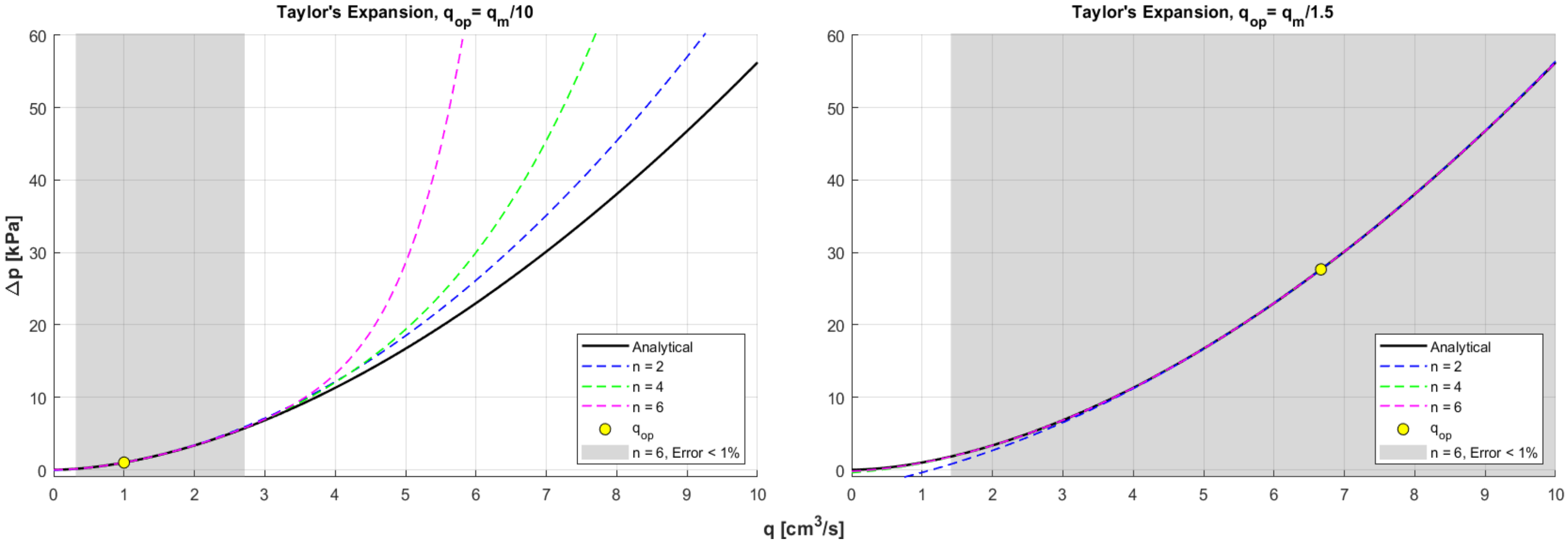

Figure 4: *Plots comparing accuracy of Taylor's expansion of order 'n' at different operating points,* ***a)*** $q_{op} = \frac{q_m}{10}$ ***b)*** $q_{op} = \frac{q_m}{1.5}$

- Fig. 4a & 4b demonstrate the dependence of accuracy of Taylor's expansion on q_{op}.
- For q_{op} close to zero, region with error < 1% is very small.

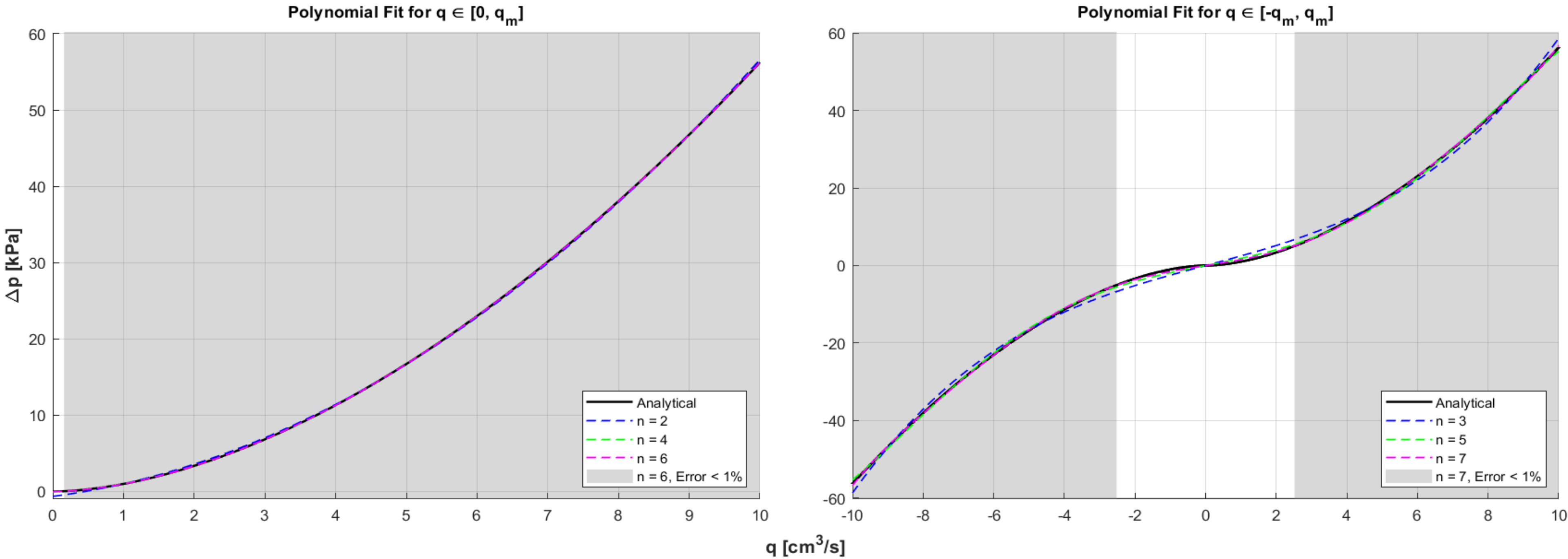

Figure 5: *Plots comparing accuracy of least-square polynomial fit of order 'n' for* ***a)*** *Positive values of flow, q* ***b)*** *complete domain of flow, q*

- Polynomial fitting better than Taylor's expansion but problem of low accuracy near $q\sim0$ region remains
- Fig. 5a formulation requires variable transformation during flow reversal.

Objective 1c

Identification of flow nature & calculation of inertance, resistance for experimental data:

Calculation of approximate inertance using $\Delta p(t)$ values for $q(t) = 0$

Identification of flow nature

a) Fast Fourier Transform (FFT) –

FFT of $\Delta p(t)$

If amplitude of first few odd harmonics, $3f, 5f, \ldots$ is significant

Yes: Turbulent Flow

No: Laminar Flow

b) Fluid resistance Pressure–

Calculate, $\Delta p_R(t) = \Delta p(t) - \Delta p_I(t)$, using approximate inertance

If turbulent, $\Delta p_R \sim q(t)^{1.75}$

If laminar, $\Delta p_R \sim q(t)$

Calculation of resistance → Curve fitting of experimental data using least-squares method

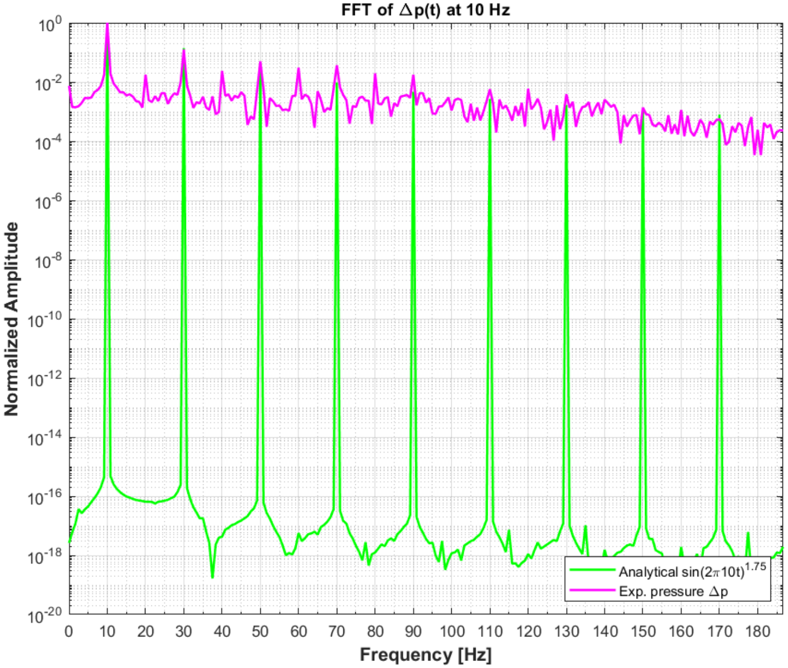

Figure 6a: *Comparison of FFT of observed & analytical $\Delta p(t)$ for excitation frequency of 10 Hz.*

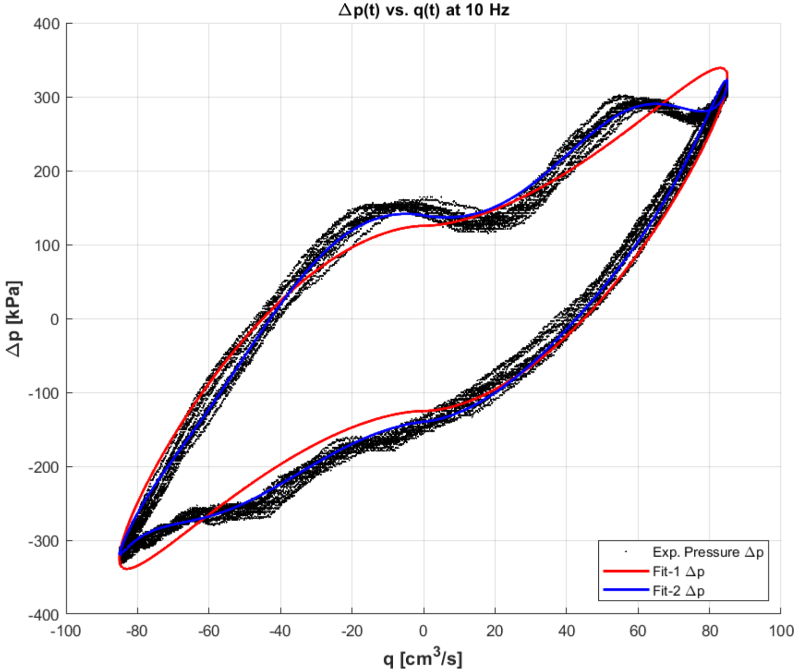

Figure 6b: *Plot comparing Δp $vs.q$ curves for observed & fitted data for excitation frequency of 10 Hz.*

- Presence of peaks at odd-harmonics in Fig. 6a suggests that turbulent flow conditions exist.
- Fit-1 : Turbulent formulation, Fit-2 : Turbulent formulation + Extra harmonic terms.
- Fit-2 represents the experimental data more accurately than Fit-1.

Objective 2

Investigate the physics of flow when a leakage path is also present in addition to inertia track

- Presence of a leakage path affects the dynamic characteristics of a bushing.
- Leakage path can be a short passage (or) orifice-like.
- Source of non-linearity in the system.
- Influence of a leakage path in conjunction with inertia track on bushing's damping properties is unknown
- Approach:
  - Incorporate a leakage path in simulation model for various configurations.
  - Analyze pressure data with leakage path unblocked & compare it to the blocked case.

Problems Faced

- Range of accurate polynomial approximation for turbulent flow is limited.
- Exact flow conditions & source of non-linearities unknown in hydraulic bushing.
- Experimental data not falling under specific regime, laminar or turbulent.
- Restricted access / lack of literature on dynamic oscillatory flows.

Plans

- Recheck FFT procedure for numerical artifacts (if any).
- Investigate why additional harmonic terms improves accuracy.
- Perform similar parameter identification analysis for more data.
- Incorporate a transitional flow resistance model for the fluid-parameters estimation.
- Getting started with studying the physics of including short leakage pathways.

Appendix

<u>Notation</u>

p = Pressure

q = Volumetric Flow Rate

f = Excitation Frequency

t = Time

I = Fluid Inertance

R = Fluid Resistance

k = Proportionality Constant

ρ = Bushing fluid density

l = Length of bushing's inertia track

A = Area of bushing's inertia track

<u>Subscripts</u>

m = Amplitude (zero-to-peak)

I = Inertance

R = Resistance

L = Laminar

T = Turbulent

O = Orifice

op = Operating Point

<u>Abbreviations</u>

FFT = Fast-Fourier Transform

Lessons Learned:

- Delivering talk/presentations skills.
- Preparing for non-technical topics & engaging in group discussions.
- Modelling mechanical systems through a lumped parameter approach.
- Approach towards non-linear problems & analyzing data in different domains.

Bibliography

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[5] Doebelin, E. (1998). System Dynamics: Modeling, Analysis, Simulation, Design (1st ed.). CRC Press. https://doi.org/10.1201/9781482269895