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ABSTRACT

Metering technology offers a number of possible options for the measurement of compressible natural gas (CNG). However, the accuracy of these measurements is dependent on various dynamic factors and fluid parameters. To avoid flow measurement from such dynamic errors, a new technique or novel concept of flowmeter is needed for measuring CNG. One of the options is to use natural force phenomenon that could be derived from fundamental physics, a force known as coriolis. It is used in mass flowmeter design that uses vibration tubes to guide and measure fluid or gas based on coriolis force. The motivation behind the research is to develop and apply coriolis in an embedded FieldPoint controller proclaimed as an inferential coriolis. The major challenge is to find a suitable algorithm for coriolis in the form of a mathematical model that could measure mass and mass flowrate of CNG with maximum permissible error. To define such system, an experimental approach known as System Identification (SYSID) theory is used. Performance of inferential coriolis is tested on experimental natural gas test rig which could be summarized into three areas: single pressure flow; continuous pressure flow; multi pressure flow with disturbances. When experiment was conducted, mass flowrate was measured using inferential coriolis and a commercial flowmeter from a manufacturer i.e., Micro Motion. To validate both methods, a load cell was used as the reference. Details evaluations of three pressure flow scenarios namely the single pressure flow, the continuous pressure flow, and the multi pressure flow for a CNG refueling system are presented. From percentage error analyses, it shows that in all measurements the inferential coriolis have less error compares to commercial coriolis manufactured by Micro Motion. The findings demonstrate the viability of the SYSID approach to provide a solution to the modeling of an inferential coriolis, and confirm the qualitative behavior of the inferential coriolis in response to the different flow measurements.

ABSTRAK

Terdapat pelbagai teknologi pengukuran untuk mengukur gas asli termampat. Walau bagaimanapun, ketepatan pengukuran bergantung kepada pelbagai faktor dinamik dan parameter bendalirnya. Untuk mengelakkan pengukuran daripada kesalahan dinamik tersebut, satu teknik baru untuk pengukuran bendalir gas asli termampat diperlukan. Salah satu daripadanya ialah dengan menggunakan tenaga dari kejadian alam semulajadi yang boleh ditafsirkan secara ilmu fizik, iaitu kejadian tenaga Coriolis. Tenaga ini telah digunakan dalam pembentukan alat penyukatan jisim bendalir yang berasaskan tiub gegaran untuk mengarah dan menyukat bendalir atau gas menggunakan tenaga Coriolisnya. Motivasi dalam penyelidikan ini, adalah untuk mengaplikasikan tenaga Coriolis tersebut dalam sebuah alat pengawal FiedPoint, yang bakal dipanggil coriolis inferens. Masalah utama untuk menghasilkan alat ini ialah untuk mencari algoritma yang sesuai untuk Coriolis dalam bentuk model matematik yang dapat mengukur jisim dan halaju jisim gas asli termampat dengan ralat terbesar yang dibenarkan. Untuk mendefinisikan sistem tersebut, kaedah ujikaji makmal telah digunakan yang dipanggil Teori Identifikasi Sistem. Penilaian teknik coriolis secara inferens ini telah diuji dalam makmal, yang boleh diringkaskan kepada tiga ujikaji iaitu, ujikaji dalam satu tekanan arah, ujikaji dalam tekanan yang berterusan atau selanjar, dan ujikaji dalam pelbagai tekanan dengan gangguan. Untuk perbandingan, halaju jisim gas asli dalam ujikaji tersebut telah diukur secara coriolis inferens dan alat penyukatan yang lebih komersil iaitu Micro Motion. Untuk pengesahan pula, sebuah alat penimbang turut digunakan. Penilaian lengkap untuk senario ujikaji satu arah tekanan, tekanan yang berterusan dan pelbagai tekanan juga dilaporkan. Melalui analisis peratus ralat pula, didapati coriolis inferens telah menghasilkan ralat yang lebih sedikit berbanding Micro Motion. Penemuan ini menunjukkan keupayaan kaedah Teori Identifikasi Sistem dalam menghasilkan penyelesaian untuk coriolis inferens, dan membuktikan sifat kualitatif coriolis inferens dalam pelbagai perbezaan penyukatan bendalir.

LIST of PATENTS

1. Malaysia Patent: Method and System for calibration of mass flow measurement for volumetric flow measurement device
   Application no: PI20054276
   Prof. Dr. V.R. Radhakrishnan
   Assoc. Prof. Dr. Mohamed Ibrahim Abdul Mutalib
   Mahidzal Dahari

2. Malaysia Patent: NGV refueling switching strategies optimization
   Application no: PF20705034
   Assoc. Prof. Dr. Mohamed Ibrahim Abdul Mutalib
   Assoc. Prof. Dr. Nordin Saad
   Mahidzal Dahari

LIST of PUBLICATIONS

1. N.A. Hisam, **M.Dahari**, M.I.A. Mutalib, and R. Ramlan, "Use of Suitable Equation of State for Conversion of Volumetric to Mass Flowrate for NGV Refueling Equipment," *Journal of Institute of Engineers Malaysia (IEM).*, Sept 2006.

2. N.Saad, **M. Dahari**, and M.I.A. Mutalib, "Time-optimal control of natural gas vehicle refueling requiring switchings of multi-pressure banks," *International Journal of Control, Automation and System - Korean Institute of Electrical Engineers*., 2008 (manuscript under review).

3. **M.Dahari**, N.Saad, M.I.A. Mutalib, and N.A. Hisam, "Design and Implementation of a Minimum Switching Time Transitions for NGV Refueling," *Paper presented in NGV2006 Conference*., Cairo, Nov 2006.

4. **M.Dahari**, N.Saad, and M.I.A. Mutalib "Implementation of System Identification to the Modeling of Meterless NGV Refueling Dispenser," *Paper presented in ANGVA2007 Conference*., Bangkok, Oct 2007.

5. **M.Dahari**, N.Saad, and M.I.A. Mutalib, "Inferential Coriolis Flowmeter for NGV Refueling using System Identification," *Paper presented in 1st National Postgraduate Conference on Engineering, Science and Technology*., University Technology PETRONAS, March 2008.

6. **M.Dahari**, N.Saad, and M.I.A. Mutalib, "Development of Meterless NGV Refueling System," *Paper presented for 4th Biannual Postgraduate Research Symposium*., Universiti Teknologi PETRONAS, Feb 2007.

7. **M.Dahari**, N.Saad, and M.I.A. Mutalib, “Development of Inferential Coriolis Flowmeter for NGV Refueling using System Identification,” *Paper presented for 5th Biannual Postgraduate Research Symposium.*, Universiti Teknologi PETRONAS, July 2007.

8. **M.Dahari**, N.Saad, and M.I.A. Mutalib, “Development of Inferential Coriolis Flowmeter for NGV Refueling using System Identification” *Paper presented for 6th Biannual Postgraduate Research Symposium.*, Universiti Teknologi PETRONAS, Jan. 2008.

9. **M.Dahari**, N.Saad, and M.I.A. Mutalib, “System Identification and Parameter Estimation of Coriolis Flowmeter,” *Paper presented for 7th Biannual Postgraduate Research Symposium.*, Universiti Teknologi PETRONAS, June 2008.

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LIST of ABBREVIATIONS

Words	**Abbreviation**
Universiti Teknologi PETRONAS	UTP
Compressed Natural Gas	CNG
Pressure-Volume-Temperature	PVT
International Association for Natural Gas Vehicles	IANGV
European Natural Gas Vehicle Association	ENGVA
Asia Pacific Natural Gas Vehicles Association	ANGVA
System Identification	SYSID
Matrix Laboratory	MATLAB
Laboratory Virtual Instrumentation Engineering Workbench	LABVIEW
Coriolis Mass Flowrate	CMF
General Linear	GL
Autoregressive Exogeneous Input	ARX
Autoregressive Moving Average with Exogeneous Input	ARMAX
Output-Error	OE
Box-Jenkins	BJ
Numerical Algorithm for Subspace State-Space	N4SID
Akaike’s Information Criterion	AIC
Final Prediction Error Criterion	FPE
Minimum Data Length Criterion	MDL
Least Mean Square	LMS
Normalized Least Mean Square	NLMS
Recursive Least Squares	RLS
Kalman Filter	KF
Time Optimal Control	TOC
Advance Natural Gas Dispenser	AND

NOMENCLATURES

v : Velocity, ms^{-1}

M : Moment

F : Force, N

ω : Angular velocity, ms^{-1}

S_1,S_2 : Time delay, s

f : frequency, Hz

m : Mass, kg

$\bar{v}$: Average velocity, ms^{-1}

L : Distance, m

a : Acceleration, ms^{-2}

r : Radius, m

ρ : Density, kg.m^{-3}

A : Area, m^{2}

L : Length, m

τ : Time, s

W : Mass flowrate, kg.s^{-1}

T : Torque, N.m

V : Velocity, m^{3}

ϕ : Angular deflection

θ : Sets of model parameters

K : Elastic modulus

T : Period, s

u : Input

y : Output

v : Disturbance

e : Zero mean white noise

λ^2 : Variances

$G(q^{-1},\theta)$: Deterministic part

$H(q^{-1},\theta)$: Stochastic part

q^{-1} : Backward shift operator

q^{-k} : Number of delay samples

n_a, n_b, n_c, n_d, n_f : Model orders

$x(n)$: State vector

N : Number of data points

p : Number of parameters in the model

$V_n(\hat{\theta})$: Index of prediction error

$\varepsilon(k)$: Residual or prediction error

$\hat{y}(k)$: Model output

α : Step size

$f(\theta^{(i)})$: Search direction

$\psi(t,\theta)$: Gradient vector

ζ : Instruments variables

$\vec{w}(n)$: Parametric vector

$\vec{\varphi}(n)$: Data vector

$\hat{y}(n)$: Predicted response

$J(n)$: Cost Function

$\vec{K}(n)$: Gain vector

λ : Forgetting factor

$^{\#}$: Pseudo inverse

p : Past horizon

f : Future horizon

Γ_f : Extended system observability matrix

X : Kalman state

Z_m : Zeroes

P_n : Poles

k : Gain

^{T} : Transposed variables