# Coriolis Flow meter: A Review from 1989 to 2014

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***Abstract*—A consolidation of literature indicating the advances in the field of mass flow measurement is presently not available. Last published review paper on Coriolis mas flow meter (CFM) was in 2006. This work is an attempt is made to summarize the available works on Coriolis mass flow meter. The literature is classified into three major groups. The first group gives the summary of construction and testing of CFM. The second section reviews the numerical modelling and FE analysis. The effect of fluid flow and flow dynamics are discussed in the third section**

***Keywords—coriolis mass flow meter; construction;testing; finite element analysis; modelling; flow pulsation effects***

## I. INTRODUCTION

Coriolis mass flow meter got its wide acceptance due to its direct measurement ability of the mass flow rate of a fluid. This measurement is generally independent of effects like pressure, temperature, density etc. It works on the correlation of mass flow rate to phase shift between any two points in the pipe vibrating in its fundamental frequency. The effect of fluid structure coupling, pipe curvature, Coriolis effect, geometric as well as material nonlinearities are highly critical in efficient design. Coriolis flow meters are mainly of two types, straight tubes and curved tubes. Mass flow meters have applications in transportation of fluids and gases in industries like petroleum, chemical, food and beverages, automotive etc.

## II. OBJECTIVE

The dynamics of pipes conveying fluids is a matter of extensive study from 1950. These studies are targeted to the effects of the fluid velocity, pressure, density, tube geometries and boundary conditions on the natural frequency and the stability of the pipe systems and helped in the formulation of dynamics of Coriolis mass flow meters. The first application of the Coriolis effect for mass flow measurement was proposed in early 1950's. The experimental studies on Coriolis flow meter was introduced in 1960's. Since the early 1980's the interest in Coriolis mass flow meters has been increasingly and widely accepted in many industries. The earlier reviews were published by Backer in 1994 and by Atkin in 2006. Here an attempt is done to summarize of available works on Coriolis flow meter for the last 25 years. The study is conducted in three different areas:

1. Construction and Testing
2. Modelling and Analysis
3. Effects of Fluid Flow

## III. REVIEW ON CORIOLIS MASS FLOW METER

### A. *Construction and Testing:*

In this section, the papers regarding the construction and testing of different configurations of Coriolis mass flow meter is considered.

The modelling of Coriolis flow meters with U tube formulation and straight tube formulation was presented by G Sultan [1, 2]. For the modelling of the U tube configuration [1], the formulation is based on theory of vibrating beams. The concept behind the assumption was that any geometry can be constructed by the connecting a number of straight tubes serially. The equations for a curved pipe is also presented. An experimental proof for the formulation is also suggested for this formulation. But the study also have limitations like the assumption of free undamped vibration for the tube, which is an idealisation. A single straight tube is modelled and analysed based on the theory of vibrating beams [2]. Modelling of added mass is done by considering the masses of electromagnetic drives and detectors as concentrated mass.

Cascetta [3, 4] suggested design modification of straight tube flow meters. A prototype (DIME 1) of straight tube flow meter with elastic suspension for commercial flow meter [3]. The prototype evaluation shows this construction is useful for many industrial application but the studies with stiffness, damping and the asymmetry caused by these two are not thoroughly studied. Some fluid dynamics problems with shape and dimensions of tubes used are also reported. Later a modified prototype (DIME 2) which answers to the fluid dynamics problem is suggested in [4]. The mathematical model for this formulation is also presented. The prototype DIME 2 is advanced than DIME 1 and answered many problems related with first, but sensitivity to external vibration is not included in this paper.

M P Henry et al [5]. presented an implementation of new Coriolis flow meter transmitter. The transmitter have many advantages like high-precision control of flow tube operation even at very low amplitudes, high precision, high speed measurements etc. some studies like investigation of the dynamic measurement effects and its physical modelling, to be extended to the impact of frequency and phase modulation etc. are left unanswered. Al-Khamis et al [6] presented a performance evaluation of three type of Coriolis mass flow meters – U tube, modified U tube and straight tube. The results of this evaluation is helpful in selecting the type of flow meter in industries. A discussion on the technologies of mass flow measurement and Coriolis mass flow meters are presented by Basrawi [7]. A comparison of the Coriolis mass flow devices versus conventional volumetric flow measurement techniques. Some useful information regarding the selection of flow meters presented.

Experimental results on various configurations of Coriolis flow meters like Straight tube, S, L, U and step is presented by Gupta et al [8].Based on parameters like position of sensors, geometry, material properties, etc., the sensitivity of flow meter is measured and presented. Different materials like Aluminium and PVC is used for constructing the configurations and water is taken as working fluid. J. Hemp and J. Kutin [9] presented study on errors in readings of Coriolis flow meter due to compressibility. The compressibility errors may occur due to flow rate and density. Here the error estimation is limited only to straight beam type. Other types like shell is not included in this study. S Wang et al [10] presented the development of a modelling tool for rapid dynamic response measurement using Coriolis meter. Finite element modelling capability of this tool helps to simulate the flow tube and pseudo data are generated. Meter response to flow steps, ramps and pulsations are investigated. Shape is not a constraint for the modelling. The dynamic response of the Coriolis mass flow meters for the validation of available results was experimentally demonstrated by Clark and Cheesewright [11] and generated user outputs by using data sampling and signal processing algorithms.

A detailed work on the factors affecting the accuracy, precision and robustness of Coriolis mass flow meter is presented by Enz [12]. The effects of fluid pulsation, imperfect actuator and detector are studied and the change in accuracy is presented. For studying the effect of imperfect velocity profile, a FE/FV model of a vibrating fluid conveying pipe is used. The work is analytical and experimental validation is needed. Sharma et al [13] presented the results of experiments on different types of copper U tubes for an indigenously developed setup of Coriolis mass flow sensor integrated with virtual instrumentation. Passive vibration isolation technique is used for the installation of set up. The studies are concentrated on the role of different factors like *L/d* ratio, sensor location, drove frequency etc. on the accuracy of Coriolis mass flow meter. For creating a predetermined resonance frequency, the application of piezoelectric element is suggested by Shanmughavalli et al [14]. The piezoelectric is used as a sensor and is placed at different location for actuation and sensing and the results were compared. Advantages of piezoelectric sensors like superior signal-to-noise ratio, high-frequency noise rejection, compactness and sensitivity over a large strain bandwidth and ease of embeddability are considered. Phasor control for operating a Coriolis mass flow meter in two different frequencies is detailed by H Rock [15]. The possibility of simultaneous operation of mass flow meter in the Eigen frequency of first and second mode is discussed. The discussion is on analytical method and the experimental validation can is possible as future studies.

The above papers give an in-depth knowledge about the construction and testing of Coriolis flow meters. Some literature which describe the construction details and published prior to 1989 are not discussed here.

*B. Modelling and Analysis*

In this section, the papers related to mathematical modelling and analysis using finite element method is considered. The work completed so far and the gap areas are discussed here.

The mathematical model of a simple straight tube Coriolis meter is suggested by Cascetta [16]. The necessary equations are formulated. Later the practical model also developed [4]. Friedman [17] presented the finite element analysis of simple two node Timoshenko beam element with shear deflection and axial forces. The formulation was based on Hamilton's principle for avoiding shear-locking and two shape functions – cubic and Lagrangian – for transverse and rotational displacements. Predictions on displacements and natural frequencies were presented. Stack and Cunningham [18] presented the design and analysis of Coriolis flow meter using the commercial software MSC/NASTRAN. Here low stress designs are suggested to preclude fatigue failure. The paper explains the advantages of the commercial software MSC/NASTRAN in design and analysis.

A parallel finite element simulation of compressible and incompressible flow is suggested by Tezduyar et al [19] . The use of parallel computing for solving large problems is reported with example. The use of I-DEA MATLAB tool box I-MAT and MATLAB in the design of Coriolis mass flow meter is explained by Cunningham and Hensely [20]. This tools are customized for a commercial mass flow meter manufactures named Micro Motion Inc. The calibration factors for various installation effects is simulated by Holm et al [21]. The simulation is carried out using computational fluid dynamics (CFD). The simulation effects studied for single straight tube and single or double elbow configurations of piping. Customization of the tool for any piping geometry is suggested. Mittal and Tezduyar [22] presented a finite element simulation of three dimensional incompressible flow considering fluid structure interactions. High speed computation facilities are used to solve the equations. The models of flexible cantilever beam subjected to 3D flow, flow past a stationary rectangular wing and flow past a wing in flapping motion are considered and results are presented. The beam formulation is made using Euler – Bernoulli beam theory which needs $C^1$ continuity. If it is modelled using Timoshenko beam theory $C^0$ continuity is sufficient.

A finite element code for the simulation of Coriolis flow meter response to flow pulsations is presented by Belhadj et al [23]. A 3-D model of straight tube Coriolis flow meter is developed with consideration to shear deflection and axial forces. A comparison is presented with available results and data from a commercially available flow meter and this work suggests that the reports of changes in meter calibration due to certain frequencies of flow pulsation represent errors in signal processing rather than fundamental changes in the meter characteristics. To understand the dynamics of fluid filled pipe, a finite element model using axisymmetric shell element and one dimensional fluid element was proposed by Hansson [24]. Numerical modelling and evaluation of symmetric element and unsymmetric elements were explained. Schafer [25] presented a multi-grid finite volume method for the coupled fluid-structure interaction problems in complex geometries and this method can reduce the computational time and accuracy of the results. A single straight slender tube Coriolis flow meter is used for the study of stability boundary condition by Kutin [26]. The theoretical characteristics were derived and obtained their solution using Galerkin method. The configurations other than straight tube was not considered. The dynamics study of the fluid filled pipe using FEM was studied by J N Durrani [27] made use of nine different cases starting from empty pipe to flow with sonic velocity are studied and results obtained from commercial FE software ANSYS were presented. J Kutin et al [28] demonstrated the characteristics of a resonance-control system to maintain appropriate phase difference between detection and excitation signals in the measuring tube of a Coriolis mass flow meter using virtual instrumentation in LabVIEW environment and its theoretical simulations.

A coupled finite volume/ finite element numerical model of a straight tube Coriolis flow meter is presented by Bobovnik et al [29]. The solutions were evaluated in terms of natural frequency and phase difference as the measuring effects of fluid density and the mass flow rate. Wang et al [30] propounded a numerical model for single straight tube Coriolis flow meter clamped at both ends. They used the fluid structure interaction (*FSI*) elements characterized as mass, stiffness and damping matrices to model the measuring tube based on theories of FSI and FEM. A detailed discussion on the uncertainties associated with the FE formulations of Coriolis mass flow meter was presented by Cheesewright and Shaw [31] and pointed out that the errors occurred were not due to modelling errors, but due computer rounding errors in eigensolvers. A three dimensional coupled fluid structure model for Coriolis flow meter is put forward by Mole et al [32]. For numerical modelling FV and FE codes were used for fluid and structural modelling respectively with a straight tube configuration with a harmonic excitation force. Stangl et al [33] described a planar pipe finite element which conveying fluid with steady flow for large deformation problems for a cantilever pipe based on Euler-Bernoulli beam theory. Based on absolute nodal coordinate formulation with Lagrange's equations, the equations of motions were established and applied to multibody systems with different boundary conditions. The influence of vibration disturbance on Coriolis mass flow meter was discussed by Yak Kai et al [34] based on a double U tube Coriolis meter modelled in ANSYS making use of MATRIX27 element and analyzed the impact of vibration on flow meter. Guirguis [35] presented the modelling of a Coriolis mass flow meter for of a general plane shape pipe using direct stiffness matrix, whose elements were derived from the equation of motion and modelled the effects of flow velocity on natural frequency and the phase difference for different geometries. Hakvoort et al [36] developed a numerical model for the study of shape optimization of Coriolis flow meter and the calculation of sensitivity and performance criteria for shape parameters were discussed for a U shaped Coriolis mass flow meter.

A mathematical model for estimation of errors in measurement caused by external vibration, temperature and pressure using analytical model of U tube was suggested by Kazahaya [37]. The dynamics of beam-moving mass was explained by using FEM by Sharbati [38] with the help of a composite beam element with the effects of Coriolis and centripetal forces. For the modelling the problem, weight is taken as the moving mass, acceleration in transverse direction, Coriolis effects and a complete beam model under linear dynamics were used. Wang et al [39] suggested an analytical method for the calculation of the sensitivity of Coriolis mass flow meter based on the sensitivity principle to compare the published results of U tube and method can calculate the relative displacement at any point on any shaped tube. Two different studies on omega type tubes were presented by Patil et al [40, 41]. The response surface modelling -- a combination of statistical and mathematical modelling -- of an omega tube electromechanical Coriolis mass flow sensors [40] and analysis of variance (ANOVA) was presented. A study based on adaptive neuro-fuzzy interface system (ANFIS) tool for the performance evaluation of a omega type Coriolis mass flow sensor under different operating conditions [41] were discussed. The modelling and simulations of flexible multibody systems containing fluid conveying pipes based on FEM is proposed by Meijaard [42] and was done based on the assumptions like constant mass flow rate and a piecewise uniform cross section of pipe. Test cases were explained in two dimension (simply supported pipe) and in three dimension (U shaped Coriolis mass flow meter) and the formulation was applicable to large deformation problem. An investigation on the finite element modelling of Coriolis mass flow meter with arbitrary pipe geometries was propounded by Rouff et al [43]. The model was created based on Timoshenko beam theory in ANSYS and MATLAB incorporating the effects of unsteady flow geometry, damping, Coriolis, centrifugal and gravitational forces etc. The effects of stiffness due to fluid deflection is partly neglected in this work and for unsteady flow, the transient analysis is conducted.

### C. *Effects of Fluid Flow:*

This section consolidating the papers relating to the various effect of fluid flow and fluid pulsation in Coriolis flow meter and its measurements.

Durst [44] conducted a study on the flow in a straight pipe which rotates about an axis perpendicular to its own axis and the flow field and fluid properties are used for the analysis of vibrating pipe segment of a Coriolis flow meter, which is helpful in predicting the behavior of flow meters in two phase flow. The effect of pulsating flow on Coriolis mass flow meter was discussed by Vetter et al [45] and investigated the effects of monofrequent and polyfrequent pulsating flows developed by geared or piston type pumps using two U tube flow meters for estimating the error due to pulsation. The results of experiments conducted on commercial Coriolis mass flow meter under medium pressure conditions (>15 bars) is demonstrated by Cascetta [46] using standard flow calibration facility and diagrams for the correction of the output reading of the tested meter in terms of the operating fluid pressure and calibration curves were also presented. Based on the reports of diminishing accuracy of the Coriolis mass flow meter due to pulsation, Cheesewright and Clerk conducted an investigation on this topic [47,48] and a full analysis of a commercial flow meter using finite element method was described and an analytical solution which guides to experiment was described [47]. Another study on the identification of external factor s which affects the calibration of the Coriolis flow meter was also presented [48] based on the investigations on three different commercially available flow meters from three different manufactures and shown that except severe disturbances, Coriolis frequency errors could be overcome by the use of different algorithms in the determination of the phase difference between the sensor signals and calibration accuracy of most Coriolis meters is not affected by such inlet flow conditions as swirl, asymmetric profile or increased turbulence. Wiggert and Tijsseling [49] presented a review on fluid transients and fluid structure interactions in flexible liquid filled pipes and summarized the essential mechanisms that cause FSI, and presented relevant data that describe the phenomenon and the various numerical and analytical methods that had been developed to successfully predict FSI are described. Clark and Cheesewright [50] demonstrated an experimental investigation of effects of external vibrations on different Coriolis flow meters from different manufacturers. The effects such as creation of additional components in sensor signals, meter errors, errors due to failure of phase difference algorithm, errors due to drive frequency etc. are numerically explained in this paper and only limited experiments were carried out.

Analysis of the velocity profile effects in a shell type Coriolis flow meter modelled using axisymmetric shell elements was coined by Bobovnik et al [51] without considering the deformations due to fluid loads. The comparison of the velocity profile effects of two different straight tube configurations , beam type and shell type, were studied by Kutin et al. [52] and an open discussion were initiated. A brief study on the dynamics of fluid conveying Timoshenko pipe was conducted by Petrus [53] using the model of a cantilever beam and focused on flutter like instabilities. The eigenvalue problem was formulated via the Bubnov-Galerkin method for the non-fluid beam and the stability of the resulting equation was studied via the Routh-Hurwitz stability criteria for the linear model and the nonlinear part is kept untouched. Yang et al [54] described the investigation on the transverse vibration of a viscoelastic pipe conveying fluid with simply supported end condition. The stability condition and numerical results for the effect of viscosity and mass ratio on instability regions were also presented for material properties based on Kelvin viscoelastic model and the axial fluid flow is characterized by simple harmonic variation and is shown that the viscosity of pipe had some contribution for keeping the system stable. The design and construction of a Coriolis mass flow meter for low flow was explained by Mehendale [55] demonstrating the steel fluid interface and suggested an automated algorithm, improved tube shape sensing the flow and constructional improvements were suggested. Wang and Hussain [56] presented the pressure effects on Coriolis mass flow meters by developing a theoretical method using the linear damping model for studying undamped natural frequencies and mode shapes and experimental results with low and high pressure effects for a straight tube meter were also reported and experimental errors are not answered.

In order to avoid the underestimation during the modelling of curved beam with straight beam elements, an equivalent beam modeling method for predicting the dynamic characteristics of curved flexible pipes was presented by Kim and Lee [57] and to show the increased flexibility of curved flexible pipes due to curvature, a strain energy concept were introduced to the proposed beam model which is numerically analyzed using ANSYS. To model the problem, consideration was given only to the flexible pipes with rectangular convolutions and moderate thickness for the finite element modeling. Using the governing equation obtained in the transverse and longitudinal directions based on the nonlinear Von-Karman sense, the dynamic behavior of a pipe conveying fluid, with a sprung mass moving on it using FEM-state space approach is studied by Sadeghi [58]. The moving load including sprung and unsprung masses, linear viscous dashpot and linear spring were added to the model. For solving the system of dynamic equations, considering the simultaneous effects of flowing fluid and moving body, the Newmark-β integration scheme was employed. Enz [59] formulated a simple mathematical model of a fluid-conveying pipe and the effect of pulsating fluid flow was analyzed using a multiple time scaling perturbation analysis and a prediction on the phase shift effects due to Coriolis force and flow pulsation in vibrating fluid conveying pipes and results of numerical testing were presented. A finite element formulation for a three-dimensional piping system conveying a harmonically pulsating fluid was carried out by S H Lee [60] and a numerical method to predict the steady-state time response of the piping system was presented and the formulation was based on the theory presented by Paidoussis.

## IV. CONCLUSION

The three sections detailed above gives a brief consolidation of the works on Coriolis flow meter from 1989 to 2014. The section A consolidates and gives a summary of construction and testing studies of different configurations of Coriolis mass flow meter (CFM). Section B details the numerical modelling and finite element analysis of CFM. A summary of effect fluid flow in pipes and flow meters are presented in Section C. The work is limited to available literature only and hence some studies may have been omitted.

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## References

[1] J Sulthan, H Hemp, “Modelling of Coriolis Mass Flow Meter”, J.Sound and Vibration, Vol.l32(3), pp. 473—489 ,1989

[2] J Sulthan, H Hemp, “Straight Tube Coriolis Mass Flow Meter”, J.Sound and Vibration, Vol.3, No. 4,pp. 241-246,1992.

[3] F. Cascetta, S. della Valle, A. R. Guido and P. Vigo, “A Coriolis mass flowmeter based on a new type of elastic suspension”, Measurement Vol 7 No 4, pp. 182 – 191 Oct-Dec 1989

[4] F. Cascetta, S. Della Vallet, A.R. Guidot, S. Paganot and P. Vigo, “A new straight pipe Coriolis mass flowmeter: the experimental characterisation”, Measurement Vol 9 No 4, pp. 176—180 Oct-Dec 1991

[5] M. P. Henry,D. W. Clarke, N. Archer, J. Bowles, M. J. Leahy, R. P. Liu, J. Vignos, F. B. Zhou,"A self-validating digital Coriolis mass flow meter: an overview",Control Engineering Practice Vol 8, pp. 487-506, 2000.

[6] Mohammed N. Al-Khamis,Ali A. Al-Nojaim,Muhammad A. Al-Marhoun, "Performance Evaluation of Coriolis Mass Flowmeters", Transactions of the ASME,Vol. 124,pp. 90-94, June 2002

[7] Y S BAsrawi, “ Coriolis Mass Flow Measuring Devices”, The 49th International Instrumentation Symposium, 4-8 May 2003

[8] Pradeep Gupta, K Sreenivasan, S V Prabhu, “Tests on Various Configurations of Coriolis Mass Flow Meter”, Measurements, Vol 39, pp. 296-307,2006.

[9] J Hemp, JKutin, “Theory of errors in Coriolis flowmeter readings due to compressibility of the fluid being metered”, Flow Measurement and Instrumentation, Vol 17, pp 359–369, 2006

[10] S Wang, C Clark,R Cheesewright, "Virtual Coriolis Flow Meter: A Tool for Simulation and Design",Proc. IMechE Part C: J. Mechanical Engineering Science, Vol 220, pp.817-836,2006

[11] C. Clark, R. Cheesewright, "Experimental determination of the dynamic response of Coriolis mass flow meters",Flow Measurement and Instrumentation, Vol. 17, pp.39–47,2006

[12] S.Enz,“Factors Affecting Coriolis Flowmeter Accuracy,Precision and Robustness, Ph D Thesis,Technical University of Denmark, 2010

[13] Satish C Sharma,Pravin P Patil,Major Ashish Vasudev, S C Jain, “Performance Evaluation of an Indegeneously Designed Copper U Tube Coriolis Mass Flow Sensors” , Measurement, Vol 43, pp. 1165-1172,2010

[14] M. Shanmughavalli, M Umapathy, G Uma, “ Smart Coriolis Mass Flow Meter”, Measurement, Vol 43, pp.549-555,2010.

[15] H Rock, F Koschmieder, “Operating Coriolis Mass Flow Meter at Two Different Frequencies Simultaneously Using Phasor Control”, The 10th International Symposium Of Measurement Technology and Intelligent Instruments June 29 – July 2 2011

[16] F. Cascetta, S. Della Vallet, A. R. Guidot, S. Paganot, and P. Vigo, “A new straight-pipe coriolis mass flowmeter: the mathematical model”, Measurement Vol 9 No 3, pp. 115—123, Jul-Sep 1991.

[17] Z Friedman, J B Kosmatka, “ An improved two node Timoshenko beam element”, Computers & Structures, Vol. 47, No.3, pp. 473-481,1993.

[18] Stack C P, Cunningham T J,"Design and Analysis of Coriolis Mass Flowmeters Using MSC/NASTRAN" Unknown, 1994.

[19] T.E. Tezduyar, SK Aliabadi, M. Behr, S. Mittal, “ Massively parallel finite element simulation of compressible and incompressible flows”, Comput. Methods Appl. Mech. Engrg. 119, pp. 157-177, 1994.

[20] T J Cunningham,D P Hensley, "Using Imat and Matlab for Coriolis Flowmeter Design", Unknown, pp. 165-171,1994.

[21] M Holm,J Stang, J Delsing ,"Simulation of flow meter calibration factors for various installation effects", Measurement 15, pp. 235-244, 1995.

[22] S. Mittal, T. E. Tezduyar, "Parallel Finite Element Simulation Of 3D Incompressible Flows: Fluid-Structure Interactions", Internallonal Journal For Numerical Methods In Fluids, Vol. 21, 933-953, 1995.

[23] A Belhadj, R Cheesewright, C Clark “ The Simulation of Coriolis Meter Response to Pulsating Flow Using General Purpose FE code”, J Fluids and Str. Vol 14, pp.613-634, 2000.

[24] Hanson, Sandberg, “ Dynamic Finite Element Analysis of Fluid Filled Pipe”, Comput.Methods.Appl.Mech.Engrg, Vol 190, pp.3111-3120,2001

[25] M Schafer, I Teschauer, “Numerical Simulation od Coupled Fluid-Solid Problem”, comput.Methods.Appl.Mech.Engrg, Vol 190, pp 3645-3667, 2001.

[26] J. Kutin , I. Bajsic, "Stability-boundary effect in Coriolis meters", Flow Measurement and Instrumentation, Vol. 12, pp, 65–73, 2001.

[27] J N Durrani, “Dynamics of Pipelines with a Finite Element Method”, Ph D Thesis, University of Calgary, 2001.

[28] J Kutin, A Samreenik, I Bajsic, “ Phase-locking Control of the Coriolis Meter’s Resonance Frequency Based on Virtual Instrumentation”, Sensors and Actuators, Vol A 104, pp 86-93, 2003.

[29] G. Bobovnik, N. Mole, J. Kutin, B. Stok, I. Bajsic,"Coupled finite-volume/finite-element modelling of the straight-tube Coriolis flowmeter",Journal of Fluids and Structures Vol.20,pp. 785–800, 2005

[30] Wang, Baker, “An Advanced Numerical Model for Single Straight tube Coriolis Flow Meters,” J. Fluid. Engrng, Vol 128, pp.1346-1350, Nov 2006.

[31] R. Cheesewright, Simon Shaw, "Uncertainties Associated with Finite Element Modelling of Coriolis Mass Flow Meters", Flow Measurement and Instrumentation,Vol. 17,pp.335–347, 2006

[32] N. Mole,G. Bobovnik, J. Kutin, B. Stok, I. Bajsic, "An Improved Three-Dimensional Coupled Fluid–Structure Model for Coriolis Flowmeters", Journal of Fluids and Structures, Vol. 24,pp. 559–575, 2008.

[33] Stangle, Grestmayer, Irshik, “A Large Deformation Planar Elemnt for Pipes Conveying Fluids Based on the Absolute Nodal Coordinate Formulation”, Journal of Computational and Nonlinear Dynamics JULY 2009, Vol. 4, pp 031009-1-031009-8.

[34] Yao Kai, Zhao Jianhui, Li Fan, “Finite element Analysis of the Influence of Vibration Disturbance on Coriolis Mass Flow Meters” International Conference on Intelligent Computation Technology and Automation 2010

[35] Samer Guirguis, Fan ShangChun,"Modeling of Coriolis mass flow meter of a general plane-shape pipe", Flow Measurement and Instrumentation, Flow Measurement and Instrumentation, Vol.21, pp.40-47, 2010

[36] W.B.J. Hakvoort , J.P. Meijaard, R.G.K.M. Aarts, J.B. Jonker, J.M. Zwikker, “Modeling a Coriolis Mass Flow Meter for Shape Optimization”, The 1st Joint International Conference on Multibody System Dynamics, May 25–27, 2010, Lappeenranta, Finland.

[37] M Kazahaya, “ A Mathematical Model an Error Analysis of Coriolis Mass Flow Meters”, IEEE Transactions On Instrumentation And Measurement, Vol. 60, No. 4, pp 1163-1174, April 2011.

[38] E Sharbati, W Szyszkowski, “ A New FEM Approach for Analysis of Beams with with Relative Movements of Masses”, Finite Element Analysis and Design, Vol. 47, pp. 1047-1057, 2011.

[39] L.J. Wang L. Hua, Z.C. Zhu, P. Ye, X. Fu, "Analytical calculation of sensitivity for Coriolis mass flowmeter", Measurement, pp. 44, pp. 1117–1127, 2011

[40] Pravin P. Patil, Satish C. Sharma, S.C. Jain,"Performance evaluation of a copper omega type Coriolis mass flow sensor with an aid of ANFIS tool",Expert Systems with Applications,Vol. 39, pp. 5019–5024, 2012.

[41] Pravin P. Patil, Satish C. Sharma, Satish C. Jain, "Response surface modeling of vibrating omega tube (Copper) electromechanical Coriolis mass flow sensor", Expert Systems with Applications, Vol.39, pp. 4418–4426, 2012.

[42] J. P. Meijaard, " Fluid-Conveying Flexible Pipes Modeled by Large-Deflection Finite Elements in Multibody Systems", Journal of Computational and Nonlinear Dynamics,Vol. 9, pp. 011008-1-011008-7, 2014.

[43] J. Ruoff, M.Hodapp, H.Kück, "Finite element modelling of Coriolis mass flowmeters with arbitrary pipe geometry and unsteady flow conditions", Flow Measurement and Instrumentation, Vol.37, pp. 119–126, 2014.

[44] F Drust, H Rasziller, “Flow in a Rotating Pipe with a View on Coriolis Mass Flow Meters”, Journal of Fluids Engineering,, Vol. 112, pp 149-154, June 1990.

[45] G. Vetter and S. Notzon, "Effect of pulsating flow on Coriolis mass flowmeters", Flow Meas. Instrum.,Volume 5 Number 4, pp. 263-273 1994.

[46] Furio Cascetta, "Effect of fluid pressure on Coriolis mass flowmeter' s performance", ISATransactions 35, pp.365-370, 1996.

[47] R. Cheesewright, C. Clark, " The Effect Of Flow Pulsations on Coriolis Mass Flow Meters",Journal of Fluids and Structures Vol.12, 1025-1039, 1998

[48] R. Cheesewright, C. Clark, D. Bisset, " The identification of external factors which influence the calibration of Coriolis massflow meters",Flow Measurement and Instrumentation , Vol. 11, pp. 1–10, 2000.

[49] D C Wiggert,S Tijsseling, "Fluid transients and fluid-structure interaction in flexible liquid-filled piping",Appl Mech Rev vol 54, no 5, pp. 455-481,September 2001

[50] Robert Cheesewright, Ali Belhadj, Colin Clark, " Effect of Mechanical Vibrations on Coriolis Mass Flow Meters", Journal of Dynamic Systems, Measurement, and Control, , Vol. 125, pp. 103-113, March 2003

[51] Bobovnik, Kutin, Bajsic, "Estimation of velocity profile effects in the shell-type Coriolis flowmeter using CFD simulations", Flow Measurement and Instrumentation, Vol 16, pp 365–373, 2005.

[52] J. Kutin, G. Bobovnik, J. Hemp, I. Bajsic,"Velocity profile effects in Coriolis mass flowmeters: Recent findings and open questions",Flow Measurement and Instrumentation,Vol. 17, pp.349–358, 2006.

[53] Ryan Curtis Petrus, "Dynamics Of Fluid-Conveying Timoshenko Pipes", M S Thesis, Texas A&M University,2006

[54] Xiaodong Yang, Tianzhi Yang, Jiduo Jin, "Dynamic Stability of a Beam-Model Viscoelastic Pipe for Conveying Pulsative Fluid", Acta Mechanica Solida Sinica, Vol. 20, No. 4, pp. 350-356, December, 2007.

[55] A. Mehendale, "Coriolis Mass Flow Rate Meters for Low Flows", Ph.D Thesis, University of Twente, Enschede, The Netherlands, 2008.

[56] Tao Wang, Yousif Hussain, "Pressure effects on Coriolis mass flowmeters", Flow Measurement and Instrumentation, Vol. 21,pp. 504–510, 2010

[57] J.G. Kim, J.K. Lee, "A modified beam modeling method considering dynamic characteristics for curved flexible pipes", International Journal of Pressure Vessels and Piping, Vol. 88, pp. 262-267, 2011

[58] M Sadeghi,M H Karimi-Dona, "Dynamic Behaviour of a Fluid Conveying pipe subjected to a Moving Sprung Mass – An FEM State Space Approach, Int. J. Pressure Vessels and Piping Vol. 88, pp. 123-131, 2011.

[59] Stephanie Enz,Jon Juel Thomsen, "Predicting phase shift effects for vibrating fluid-conveying pipes due to Coriolis forces and fluid pulsation", Journal of Sound and Vibration,Vol. 330, pp. 5096-5113, 2011.

[60] Seong-Hyeon Lee, Weui-Bong Jeong,"An efficient method to predict steady-state vibration of three-dimensional piping system conveying a pulsating fluid", Journal of Mechanical Science and Technology 26 (9), pp. 2659-2667, 2012.