Universal Journal of Hydraulics **9 (2021), 16-22**
www.papersciences.com **EU Academy of Sciences (EUAS) e-Symposium**

An Overview of the Steam Generation Method in Unsteady Cascade Aeroelasticity by using Non-linear Singular Integral Equations Method

E.G. Ladopoulos
Interpaper Research Organization
Athens, GR - 106 72, Greece
eladopoulos@interpaper.org

Abstract

A modern non-linear model is further proposed and investigated, for the determination of the velocity field around a cascade of airfoils of a turbomachine. Such problem is reduced to the solution of a non-linear multidimensional singular integral equation, when considering harmonic time dependence between the motions of adjacent blades of the turbine. Thus, in order to increase the efficiency of the *Once Through Steam Generator* (OTSG) generating steam for the *Steam-Assisted Gravity Drainage* (SAGD) method of the oil sands, as well as to reduce the high Greenhaus Gas Emissions (GHG), a special turbomachine is further improved. Especially, the velocity field around a cascade of airfoils is determined, while this problem is reduced to the solution of a non-linear multidimensional singular integral equation, when considering harmonic time dependence between the motions of adjacent blades of the turbine. Consequently, a general non-linear model is studied, by proposing a modern method.

Key Word and Phrases
Non-linear Singular Integral Equations, Unsteady Cascade Aeroelasticity, Once Through Steam Generator (OTSG), Steam-Assissted Gravity Drainage (SAGD), Oil Sands, Turbomachine, Airfoil, Greenhouse Gas Emissions (GHG).

1. Introduction

Oil sands, or more technically, bituminous sands, are a type of unconventional petroleum deposit. Hence, the oil sand is either loose sand or partially consolidated sandstone containing a naturally occurring mixture of sand, clay, and water, saturated with a dense and extremely viscous form of petroleum technically referred to as bitumen. Natural bitumen deposits are reported in many countries, but in particular are found in extremely large quantities in Canada. The estimated worldwide deposits of oil are more than 2 trillion barrels and the estimates include deposits that haven't been discovered.

The crude bitumen contained in the Canadian petroleum sands is described by the National Energy Board of Canada as "a highly viscous mixture of hydrocarbons heavier than pentanes which, in its natural state, is not usually recoverable at a commercial rate through a well because it is too thick to flow." Crude bitumen is a thick, sticky form of crude oil, so heavy and viscous that it will not flow unless heated or diluted with lighter hydrocarbons such as light crude oil or natural-gas condensate. The World Energy Council (WEC) defines natural bitumen as "oil having a viscosity greater than 10,000 centipoise under reservoir conditions and an API gravity of less than 10° API".

Also, according to the study ordered by the Government of Alberta and conducted by Jacobs Engineering Group, emissions from oil-sand crude are 12% higher than from conventional oil. The most common recovery process for producing petroleum from oil sands reservoirs is known as ***Steam-Assisted Gravity Drainage (SAGD).*** In this process, steam is generated within an ***Once Through Steam Generator (OTSG)*** at a central processing facility, transported to well pads, and injected below ground into a horizontal wellbore within the reservoir. The heat supplied by the steam warms the heavy oil in the reservoir, allowing it to flow via gravity drainage into a second underlying wellbore that captures the oil/water mixture and produces it to the surface. The resultant oil/water mixture is separated, and the process water is then recycled to produce boiler feedwater for steam generation in the OTSG. Thus, the Greenhouse Gas Emissions (GHG) are higher because continuous steam generation for SAGD operations consumes significant amounts of natural gas.

SAGD was developed in the 1980s by the Alberta Oil Sands Technology and Research Authority and fortuitously coincided with improvements in directional drilling technology that made it quick and inexpensive to do by the mid 1990s. In SAGD, two horizontal wells are drilled in the oil sands, one at the bottom of the formation and another about 5 meters above it. These wells are typically drilled in groups off central pads and can extend for miles in all directions. In each well pair, steam is injected into the upper well, the heat melts the bitumen, which allows it to flow into the lower well, where it is pumped to the surface.

Consequently, SAGD has proved to be a major breakthrough in production technology since it allows very high oil production rates, and recovers up to 60% of the oil in place. Because of its economic feasibility and applicability to a vast area of oil sands, this method alone quadrupled North American oil reserves and allowed Canada to move to second place in world oil reserves after Saudi Arabia. Most major Canadian petroleum companies now have SAGD projects in production or under construction in Alberta's oil sands areas and in Wyoming.

The production of bitumen and synthetic crude oil emits more greenhouse gases than the production of conventional crude oil. A 2009 study by the consulting firm IHS CERA estimated that production from Canada's oil sands emits "about 5% to 15% more carbon dioxide, over the "well-to-wheels" (WTW) lifetime analysis of the fuel, than average crude oil."

A Stanford University study commissioned by the EU in 2011 found that oil sands crude was as much as 22% more carbon intensive than other fuels. Greenpeace says the oil sands industry has been identified as the largest contributor to greenhouse gas emissions growth in Canada, as it accounts for 40 million tons of CO_2 emissions per year.

Furthermore, during the start up phase of the SAGD, thermal and fluid communication has to be established between the injector and producer well and this typically takes several months due to lack of fluid mobility. Under a typical SAGD start up process, steam is circulated into both wells and much of the condensed steam is returned to the surface for reheating and reuse. Furthermore, during start up, steam circulates along the length of the well, condenses and gives up its latent heat, which heats the reservoir and bitumen through conduction. Both injector and producer wells operate this way at the same time during the SAGD start. It typically takes about 3 months under normal SAGD start up to heat the reservoir and bitumen between the two wells to 90°C. Normal SAGD operations then commence, with steam injected into the injector well. The latent heat from steam condensation increases the temperature of the bitumen, which then flows by gravity to the producer well where is brought to surface.

By the present study, the Start Up of the SAGD process will be improved very much. Hence, we propose the increase of the efficiency for the OTSG generating steam of the SAGD method, which will result to the big reduction of the start up time for the SAGD operations. Thus, in order to increase the efficiency of the OTSG generating steam for the SAGD method of the oil sands, as well as to reduce the high GHG, a special turbomachine is further improved. According to the proposed modern technology a two-dimensional unsteady cascade aeroelasticity is introduced for the investigation of flowfields of turbomachines generating steam. Especially, the velocity field around a cascade of airfoils is determined, while such a problem is reduced to the solution of a non-linear multidimensional singular integral equation, when considering harmonic time dependence between the motions of adjacent blades of the turbine. Consequently, a general non-linear model is investigated, by proposing a modern method.

Hence, by considering an airfoil or blade in an axial flow turbine or compressor which is running at some rotational speed, then because of the aerodynamic and structural performance, the blade has certain geometric properties defined by its length, root and tip fixation, possible mechanical attachment to other blades and by the chord, camber, thickness, stagger and profile shape which are functions of the radial coordinate. Additionally, the blade can be constructed in such a manner that the line of centroids and the line of shear centers are neither radial nor straight, but are defined by schedules of axial and tangential coordinates as functions of radius.

Over the last years several non-linear singular integral equations methods were used successfully by E.G. Ladopoulos [1] - [36] for the solution of many applied problems of petroleum engineering. Thus, by the current study, a general non-linear model is proposed for the investigation of an improved steam generator used in order to increase the efficiency for oil sand productions, as well as to reduce the existing GHG.

Finally, by the current “innovative” technology will result to:

- Reduce the startup time for SAGD operations, much less than the current 3 months.
- Control the heat transfer to the bitumen contained in the porous media between the injector and producer well, ultimately increasing the temperature of the region between the wells from a native temperature of 10°C to 90°C. At this temperature, bitumen’s viscosity is low enough to allow the bitumen to flow.
- Reduce bitumen’s viscosity to a value below 1500 cp.
- Be energetically and economically feasible
- Be environmentally sound, not creating any toxic or unsafe by-products.

2. New Methods of Unsteady Cascade Aeroelasticity by Non-linear Singular Integral Equations

The aeroelastic problem of the axial flow steam turbine will be used for a modern steam generator for the SAGD method of petroleum sands. In the turbomachine the angle of attack of each rotor airfoil at each radius r is compounded of the tangential velocities of the airfoil section due to rotor rotation and the through flow velocity as modified in direction by the upstream stator row. (Fig.1)

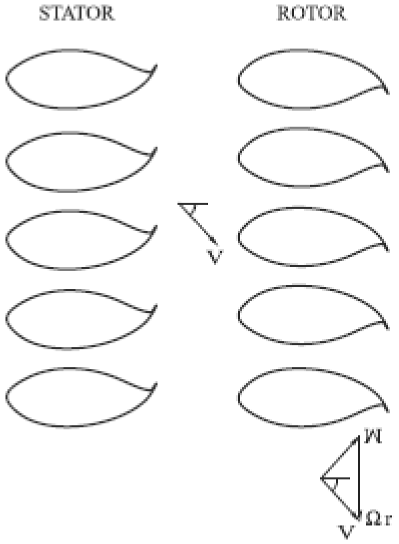

Fig. 1 Velocity triangle in an axial turbine

By considering a cascade of airfoils, then the fact that the flexible blades may be vibrating means that the relative pitch and stagger may be functions of time and also position in the cascade. Furthermore, a fundamental complication which further occurs is the necessity for treating the wakes of shed-vorticity from all the blades in the cascade and the flow under study is incompressible. (Fig. 2)

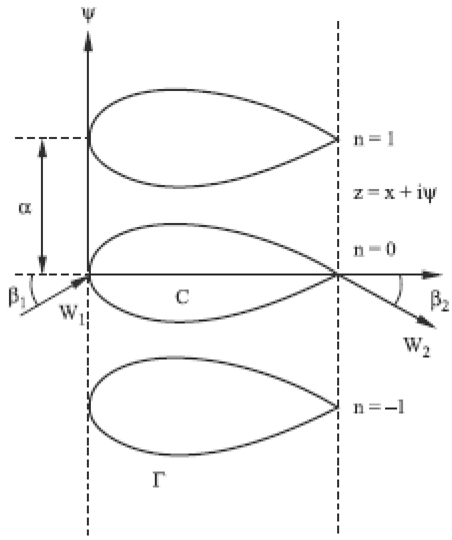

Fig. 2 A lattice of airfoils in an axial turbine

The velocities induced by an infinite column of vortices of equal strength Λ are given by the relation: [37]

$$\delta[u(z)-iv(z)]=\frac{i\Lambda}{2\pi}\sum_{n=-\infty}^{\infty}\frac{1}{Z-\zeta_n} \tag{2.1}$$

where ζ_n denotes the location of the n-th airfoil:

$$\zeta_n=\xi+inae^{-i\beta}+iY_n(\xi_n,t)+X_n(t) \tag{2.2}$$

in which t is the time and $Y_n<<a$, $X_n<<c$, with a the pitch (see: Fig 2) and c the length of the wake (Fig, 2). In addition, the point Z is on the zeroth blade:

$$Z=x+iY(x,t)+X(t) \tag{2.3}$$

and the points ξ_n in (2.2) are equal to :

$$\xi_n=\xi+na\sin\beta \tag{2.4}$$

Moreover, the harmonic time dependence between the motions of adjacent blades is given by the relation:

$$Y_n(\xi_n,t)=e^{i\pi\omega\tau}Y(\xi,t) \tag{2.5}$$

with τ the time lag.

Thus, the singular kernel in (2.1) takes the form:

$$\frac{1}{Z-\zeta_n}=\frac{1}{[x-\xi-inae^{-i\beta}+i[Y(x,t)-Y_n(\xi_n,t)]+X(t)-X_n(t)]} \tag{2.6}$$

and for infinite number of blades:

$$\sum_{n=-\infty}^{\infty}\frac{1}{Z-\zeta_n}=\frac{1}{x-\xi+i[Y(x,t)-Y(\xi,t)]}+\sum_{n=-\infty}^{\infty^*}\frac{1}{Z-\zeta_n} \tag{2.7}$$

For the thin-airfoil theory the first term in (2.7) is conventionally ignored, and therefore the remaining term can be written as follows:

$$\sum_{n=-\infty}^{\infty^*}\frac{1}{Z-\zeta_n}\approx\sum_{n=-\infty}^{\infty^*}\frac{1}{x-\xi-inae^{-i\beta}}+i\sum_{n=-\infty}^{\infty^*}\frac{Y_n(\xi_n,t)-Y(x,t)}{(x-\xi-inae^{-i\beta})^2}+$$

$$+\sum_{n=-\infty}^{\infty^*}\frac{X_n(t)-X(t)}{(x-\xi-inae^{-i\beta})^2}+\ldots\ldots \tag{2.8}$$

By combining (2.1) and (2.8) and denoting by $\lambda_a(x)$ (a=cascade spacing) the vortex strength distribution, we obtain for the unsteady induced velocities:

$$\delta[u^*(x')-iv^*(x')]\approx-\frac{\lambda_a(\xi')\delta\xi'}{2\pi c}R^2\left[\sum_{n=-\infty}^{\infty^*}\frac{e^{in\omega\tau}Y(\xi',t)-Y(x',t)}{(S-in\pi)^2}+\right.$$

$$\left.+\frac{1}{i}\sum_{n=-\infty}^{\infty^*}\frac{e^{in\omega\tau}X(t)-X(t)}{(S-in\pi)^2}\right] \tag{2.9}$$

where the variables R and S are equal to:

$$R=\pi e^{i\beta}(c/a) \tag{2.10a}$$

$$S=R(x'-\xi') \tag{2.10b}$$

and u^*, v^* are the time dependent parts of u and v.

In addition, let us replace by Q:

$$Q=1-\frac{\omega\tau}{\pi} \tag{2.11}$$

and let the special case when the blades move perpendicular to their chordlines with the same amplitude along the chord:

$$\mathrm{Y}=-c_1^*e^{i\omega t}=-c_2 \tag{2.12}$$

Also, by integrating over the chord in (2.9) we obtain the following non-linear multidimensional singular integral equation:

$$u^*(x')-iv^*(x')=\frac{R^2}{2\pi c}\int_0^1\lambda_a(\xi')\sum_{n=-\infty}^{\infty^*}\frac{e^{in\omega\tau}c_2(t)-c_2(t)}{(S-in\pi)^2} \tag{2.13}$$

which further takes the form:

$$u^*(x')=-\frac{c_2}{2\pi c}\int_0^1\lambda_a(\xi')[F-iI]d\xi' \qquad (2.14a)$$

and:

$$v^*(x')=\frac{c_2}{2\pi c}\int_0^1\lambda_a(\xi')[G+iH]d\xi' \qquad (2.14b)$$

where:

$$F+iG=R^2\,\frac{Q\sinh S\sin QS-\cosh S\cosh QS+1}{\sinh^2 S} \qquad (2.15a)$$

and:

$$H+iI=R^2\,\frac{Q\sinh S\cos QS-\cosh S\sinh QS}{\sinh^2 S} \qquad (2.15b)$$

3. Conclusions

By the present research a general non-linear model was proposed, for the determination of the velocity field around a cascade of airfoils of a turbomachine. Such problem was reduced to the solution of a non-linear multidimensional singular integral equation, when considering harmonic time dependence between the motions of adjacent blades of the turbine. Consequently, in order to increase the efficiency of the OTSG generating steam for the SAGD method of the petroleum sands, as well as to reduce the high GHG, a special turbomachine is proposed

Also, a mathematical model has been presented as an attempt to determine the properties of the OTSG turbine. The above mentioned problem was reduced to the solution of a non-linear singular integral equation, which was numerically solved by using a special software as already proposed by Interpaper Research Organization. Thus, there is a technical maturity of the proposed technique, as it based on ready software.

Such non-linear singular integral equation method will be of increasing interest in future, as these methods are very important for the solution of generalized solid mechanics and fluid mechanics problems. Modern problems of fluid and solid mechanics are much more simplified when solved by general non-linear singular integral equation methods.

Furthermore, the field of aeroelasticity in turbomachines, continues to be under active investigation, driven by the needs of steam turbine designers. Especially, the design of the new generation turbomachines will be only possible by high sophisticated non-linear computational methods. So, the non-linear singular integral equations method which was successfully used over the last years for the solution of problems of aerodynamics, fluid mechanics, hydraulics, structural analysis and fracture mechanics, etc. will be further used for the design of the next generation turbomachines, used for the SAGD method of the oil sands.

References

1. *Ladopoulos E.G.,* 'Non-linear Singular Integral Representation for Petroleum Reservoir Engineering', *Acta Mech,* ***220*** *(2011), 247-255.*
2. *Ladopoulos E.G.,* 'Petroleum Reservoir Engineering by Non-linear Singular Integral Equations', *Mech Engng Res.,* ***1*** *(2011), 2-11.*
3. *Ladopoulos E.G.,* 'Oil Reserves Exploration by Non-linear Real-Time Expert Seismology', *Oil Asia J.,* ***32*** *(2012), 30-35.*
4. *Ladopoulos E.G.,* 'Hydrocarbon Reserves Exploration by Real-Time Expert Seismology and Non-linear Singular Integral Equations', *Int. J. Oil Gas Coal Tech.,* ***5*** *(2012), 299-315.*
5. *Ladopoulos E.G.,* 'New Aspects for Petroleum Reservoir Exploration by Real-time Expert Seismology', *Oil Gas Busin. J.,* ***2012*** *(2012), 314-329..*
6. *Ladopoulos E.G.,* 'Petroleum & Gas Reserves Exploration by Real-Time Expert Seismology and Non-linear Seismic Wave Motion', *Adv. Petrol. Explor. Develop.,* ***4*** *(2012), 1-13.*
7. *Ladopoulos E.G.,* 'Non-linear Singular Integral Equations for Multiphase Flows in Petroleum Reservoir Engineering', *J. Petrol. Engng Tech.,* ***2*** *(2012), 29-39.*
8. *Ladopoulos E.G.,* 'Real-time Expert Seismology by Non-linear Oil Reserves Expert System', *J. Petrol. Gas Engn,* ***4*** *(2013), 28-34.*

9. *Ladopoulos E.G.*, ‘New Sophisticated Model for Exact Petroleum Reserves Exploration by Non-linear Real-Time Expert Seismology’, *Univ. J. Petrol. Scien.*, ***1*** *(2013), 15-29.*
10. *Ladopoulos E.G.*, 'Real-Time Expert Seismology and Non-linear Singular Integral Equations for Oil Reserves Exploration'*, Univ. J. Nonlin. Mech.,* ***1*** *(2013), 1-17.*
11. *Ladopoulos E.G.*, ‘Non-linear Real-Time Expert Seismology for Petroleum Reservoir Exploration’, *Univ. J. Nonlin. Mech.,* ***1*** *(2013), 18-29.*
12. *Ladopoulos E.G.*, ‘General Form of Non-linear Real-Time Expert Seismology for Oil and Gas Reserves Exploration’, *Univ. J. Petrol. Scien.,* ***1*** *(2013), 1-14.*
13. *Ladopoulos E.G.*, ‘Oil and Gas Reserves Exploration by Generalized Form of Non-linear Real-Time Expert Seismology’, *Univ. J. Engng Mech.,* ***1*** *(2013), 17-30.*
14. *Ladopoulos E.G.*, ‘Multiphase Flows in Oil Reservoir Engineering by Non-linear Singular Integral Equations’, *Univ. J. Fluid Mech.,***1** *(2013), 1-11.*
15. *Ladopoulos E.G.*, ‘Very Deep Drillings for Oil and Gas Reserves Exploration by Non-linear Real-Time Expert Seismology’, *Univ. J. Comp. Anal.,* ***1*** *(2013), 9-23.*
16. *Ladopoulos E.G.*, ‘Non-linear Real-Time Expert Seismology for Very Deep Drillings in Petroleum Reserves Exploration’, *Univ. J. Nonlin. Mech.,* ***1*** *(2013), 18-29.*
17. *Ladopoulos E.G.*, ‘Non-linear Seismic Wave Motion in Elastodynamics with Application to Real-Time Expert Seismology’, *Univ. J. Int. Eqns.,* ***1*** *(2013), 13-27.*
18. *Ladopoulos E.G.*, ‘Elastodynamics for Non-linear Seismic Wave Motion in Real-Time Expert Seismology’, *Int. J. Acous. Vibr.,* ***19*** *(2014), 1-8.*
19. *Ladopoulos E.G.*, ‘Non-linear Real–Time Expert Seismology by the Abiotic Theory of Hydrocarbon Generation’, *Univ. J. Petrol. Scien.,* ***2*** *(2014), 1-15.*
20. *Ladopoulos E.G.*, ‘Three-dimensional Non-linear Real-Time Expert Seismology for Oil and Gas Exploration’, *Univ. J. Petrol. Scien.,* ***2*** *(2014), 16-30.*
21. *Ladopoulos E.G.*, ‘Non-linear Real-Time Expert Seismology for Three-dimensional On-shore and Off-shore Petroleum Exploration’, *Univ. J. Non-lin. Mech.,* ***2*** *(2014), 1-15.*
22. *Ladopoulos E.G.*, ‘Three-dimensional Oil and Gas Exploration by Non-linear Real-Time Expert Seismology’, *Univ. J. Non-lin. Mech.,* ***2*** *(2014), 16-30.*
23. *Ladopoulos E.G.*, ‘Three-dimensional Multiphase Flows by Non-linear Singular Integral Equations in Petroleum Engineering’, *Univ. J. Int. Eqns,* ***2*** *(2014), 1-11.*
24. *Ladopoulos E.G.*, ‘Non-linear Three-dimensional Porous Medium Analysis in Petroleum Reservoir Engineering’, *Univ. J. Fluid Mech.,* ***2*** *(2014), 1-11.*
25. *Ladopoulos E.G.*, ‘Non-linear Real-Time Expert Seismology for Three-dimensional Abiotic Oil Generation’, *Univ. J. Fluid Mech,* ***2*** *(2014), 12-26.*
26. *Ladopoulos E.G.*, ‘Non-linear Elastodynamics by Seismic Wave Motion in Real-Time Expert Seismology’, *Univ. J. Engng Mech.,* ***2*** *(2014), 1-15.*
27. *Ladopoulos E.G.*, ‘Non-linear Singular Integral Equations & Real-Time Expert Seismology for Petroleum Reserves Exploration’, *Univ. J. Engng Mech.,* ***2*** *(2014), 16-32.*
28. *Ladopoulos E.G.*, ‘Computational Methods for Three-dimensional Analysis of Non-linear Real-Time Expert Seismology for Petroleum Exploration’, *Univ.J Comp. Anal.,* ***2*** *(2014), 1-15.*
29. *Ladopoulos E.G.*, ‘Non-linear Real-Time Expert Seismology for Four-dimensional Petroleum Exploration’, *Univ. J. Non-lin. Mech.,* ***3*** *(2015), 1-16 .*
30. *Ladopoulos E.G.*, ‘Four-dimensional Petroleum and Gas Exploration by Non-linear Real-Time Expert Seismology’, *Univ. J. Petrol. Scien.,* ***3*** *(2015), 8-23.*
31. *Ladopoulos E.G.*, ‘Non-linear Singular Integral Equations in Oil and Gas Engineering by Four-dimensional Multiphase Flows’, *Univ. J. Int, Eqns,* ***3*** *(2015), 1-11.*
32. *Ladopoulos E.G.*, ‘Petroleum & Gas Reservoir Engineering by Four-dimensional Non-linear Porous Medium Analysis’, *Univ. J. Fluid Mech.,* ***3*** *(2015), 8-18.*
33. *Ladopoulos E.G.*, ‘Four-dimensional Real-Time Expert Seismology & Non-linear Singular Integral Equations for Oil Reserves Exploration’, *Univ. J. Engng. Mech.,* ***3*** *(2015), 15-32.*
34. *Ladopoulos E.G.*, ‘Four-dimensional Petroleum Exploration & Non-linear ESP Artificial Lift by Multiple Pumps for Petroleum Well Development’, *Univ. J. Hydr.,* ***3*** *(2015), 1-14.*
35. *Ladopoulos E.G.*, ‘Four-dimensional Multiphse Flows by Non-linear Singular Integral Equations in Petroleum Reservoir Engineering’, *Univ. J. Non-lin. Mech.,* ***3*** *(2015), 17-27.*
36. *Ladopoulos E.G.*, ‘Elastodynamics in Four-dimensional Non-linear Real-Time Expert Seismology’, *Univ. J. Struct. Anal.,* ***3*** *(2015), 1-15.*
37. *Ladopoulos E.G.*, ‘Non-linear Singular Integral Equations Analysis for Unsteady Cascade Aeroelasticity applied in Turbomachines’, *Arch. Mech..,* ***65*** *(2013), 45-53.*