Control of Flow Induced Vibration using Nonlinear Energy Sink

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Abstract:- *Flow induced vibration is very dangerous phenomena in mechanical systems whose parts undergo fluid-structural interaction. Various examples like aircraft wing flutter, bridge flutter, vortex generation in the engine cylinder, vibration in underwater pipelines, pipe oscillations in heat exchangers etc. can be cited. This work concerns itself with the use of Nonlinear Energy Sink (NES) to control such Flow induced vibration (FIVs). The use of NES to control FIVs has already been attempted but these works do not consider the self-excited nature of the FIV because of the interaction between wake and solid structure. In contrast, this work considers an NES attached to a cylinder in cross-flow which is modeled by using wake oscillators developed by Facchinetti et.al. [3]. The performance of NES and stability of the system is studied and compared to that in forced models. The effect of system parameters on the performance of NES are also integrated. It is shown that NES is capable and of controlling the oscillations of the main structure. It is also shown that considering the wake-solid interaction imposes the performance of the NES.*

Keyword: Flow induced vibration, Nonlinear Energy Sink, Fluid-structure interaction, Chaos, Quasiperiodic, Wake

1. INTRODUCTION

Flow induced vibration is a critical phenomenon that occurs when the structure is kept in the cross flow of fluid. Vortices are shed up and down which creates fluctuating lift forces on the structure causes structure to oscillate in the transverse direction. In the case when vortex shedding frequency matches with structure natural frequency then it vibrates at high amplitude, this is called as "lock in" phenomena or "synchronization". Such large amplitude oscillations of structure reduce fatigue strength of the structure and create a bad performance of the system, and affects the safety of the structure. So this type of problem can be understood by keeping the cylinder in cross fluid flow. Nonlinear Energy Sink (NES) is a vibration controlling system which is using a nonlinear spring, mass, and damper. Nonlinear spring is having essential cubic nonlinearity. Earlier Linear dampers or Tuned mass dampers was used to control FIVs but Tuned mass dampers are not much efficient to control FIV. NES is more effective to control flow induced vibrations problem. NES can be installed in a strongly nonlinear vibratory system like flow induced vibration and is working on energy absorption mechanism. At higher amplitudes, NES is activated and energy is transferred from structure to NES and it is irreversible energy transfer mechanism.

1.1 Literature review

P.W. Bearman et.al, [6] worked on vortex induced vibrations of bluff bodies, they found the interaction between cylinder like slender structures kept in the cross flow in 1984. S.-S. Chen et.al, [8] worked on Flow induced vibrations of cylindrical structures in 1987. C.H.K Williamson, A. Roshko et.al [7] worked on vortex formation in the wake of an oscillating cylinder. They studied how the wake is affecting the structure and dynamics of the system in 1988. M.L. Facchinetti et.al [4] studied how waves or vortex is generating around the cables in 2001. M.L. Facchinetti et.al [3] studied the strong coupling between the wake and structure oscillator and investigated the performance of the system in 2004. Tumkur et.al [9] studied the suppression of flow induced vibration in 2011. Ali H. Nayfeh et.al [5] studied and investigated control of flow induced vibration using a nonlinear energy sink in 2014. He studied qualitative responses as parameters of NES are changed. He found out there are a different type of response like periodic, quasiperiodic, chaos or strange attractor.

1.2 Objective

The main objective of this work is to control of flow induced vibration using NES. Facchinetti et.al [3] modeled FIV considering the wake oscillator (bidirectional coupling) which means cylinder and wake interact with each other, and Nayfeh et.al [5] modelled FIV using normal forced vibration model. In this work, I would like to study the system using wake oscillator coupled with the forced model. These study is indicates stability of the system.

2. MATHEMATICAL MODELING & RESULTS

2.1 Mathematical model

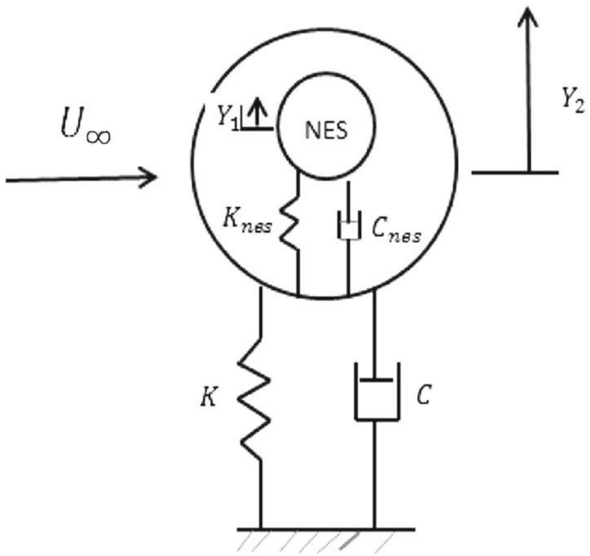

Fig.1- Model of Flow induced vibration

Consider the cylinder with non-linear energy sink kept in a cross flow of fluid at Re=106 which creates fluid forces in the transverse direction this causes the cylinder to vibrate. Considering the case in which an NES is attached to the main structure.

First considering two oscillators as a cylinder and nonlinear energy sink the governing equations of motions in non-dimensional form as follows,

$$\begin{aligned} &(1-\mu)\ddot{Y}_2 + C\dot{Y}_2 + KY_2 + C_{nes}(\dot{Y}_2 - \dot{Y}_1) + K_{nes}(Y_2 - Y_1)^3 = S \\ &\mu\dot{Y}_1 + C_{nes}(\dot{Y}_1 - \dot{Y}_2) + K_{nes}(Y_1 - Y_2)^3 = 0 \end{aligned} \quad (1)$$

Now considering the case wake oscillator, cylinder and NES and writing the governing equations as follows,

$$\begin{aligned} &(1-\mu)\ddot{Y}_2 + C\dot{Y}_2 + KY_2 + C_{nes}(\dot{Y}_2 - \dot{Y}_1) + K_{nes}(Y_2 - Y_1)^3 = S \\ &\ddot{q} + \varepsilon(q^2 - 1)\dot{q} + q = F \\ &\mu\dot{Y}_1 + C_{nes}(\dot{Y}_1 - \dot{Y}_2) + K_{nes}(Y_1 - Y_2)^3 = 0 \end{aligned} \quad (2)$$

Coupling parameters are as follows,

$S = M\,q$
$F = A\,\ddot{Y}_2$

where,

Y2 = cylinder amplitude
Y1 = non-linear energy sink amplitude
q = wake amplitude
μ = mass ratio
C = cylinder damping coefficient

C_{nes} = non-linear energy sink damping coefficient
K = cylinder stiffness
K_{nes} = non-linear energy sink stiffness
S = force acting on the cylinder by the wake
F = force acting on the wake by the cylinder
Values for coupling con`stants M and A are taken from Facchinetti model [3] and
M = 0.0002
A = 12
ε = 0.03
Where values for stiffness and damping are taken from Nayfeh model [5]
C = 0.0026
K = 1.13404

2.2 Results and discussion

To investigate the effects on the system and performance of the NES for controlling the FIV, we performed the numerical simulations at Re = 106. We first considered the effect of mass ratio on the system response.

2.2.1 Effect of mass ratio of the NES and cylinder

Considering the variation in mass ratio and analyzing the response of the system of Eq^n.2 and validating with Eq^n.1
First taking μ = 0.01 we observe that response of cylinder amplitude $Y2$ = 0.18 and NES amplitude $Y1$ = 0.35 which is much lower than that of (Eq^n.1) of cylinder amplitude $Y2$ = 0.38 and NES amplitude $Y1$ = 0.6 which can clearly see from the Fig.4.
If we change to μ = 0.02 we observed that there is no qualitative change in the system response but there is a quantitative change in amplitudes of cylinder and NES. $Y2$ = 0.005 and $Y1$ = 0.025 which is still lower than Eq^n.1
At μ = 0.25 suddenly system going to chaos and oscillates at amplitude is varying from $Y2$ = 0 to 1 and $Y1$ = 0 to 2. So in practice we have to keep mass ratio as small as possible it means to maintain the mass of NES relative to the Cylinder.

μ = 0.01:

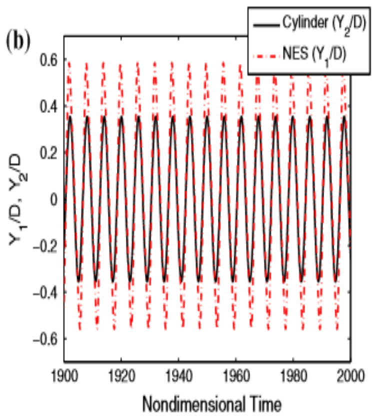

Fig.2- Time domain (Eq^{n}1)

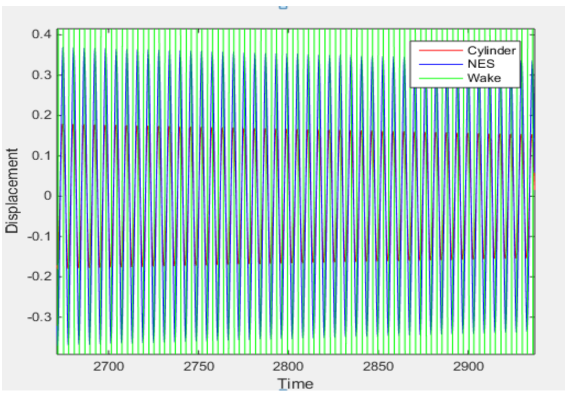

Fig.3- Time domain (Eq^{n}2)

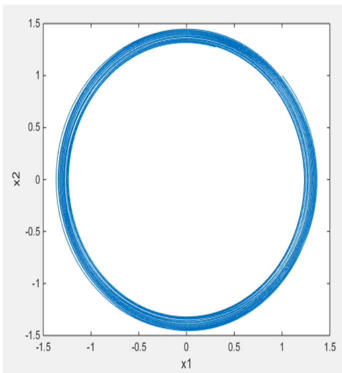

Fig.4- Phase portrait (Eq^{n}2)

μ = 0.02:

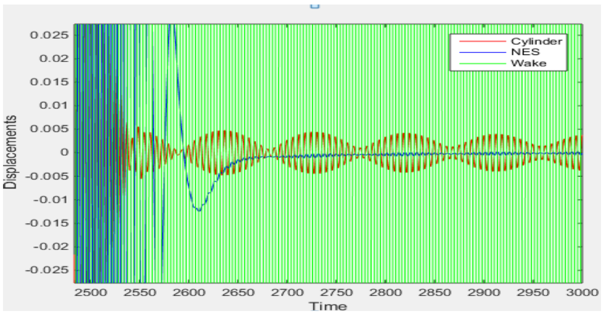

Fig.5- Time domain (Eq^{n}2)

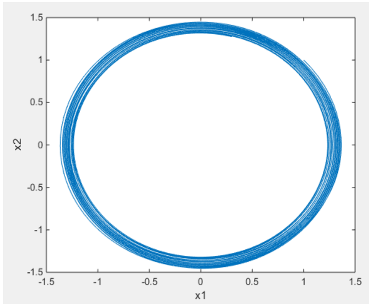

Fig.6- Phase portrait (Eq^{n}2)

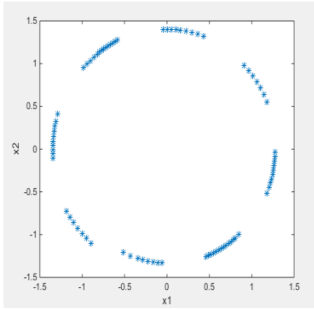

Fig.7- Poincare section (Eq^{n}2)

μ = 0.25:

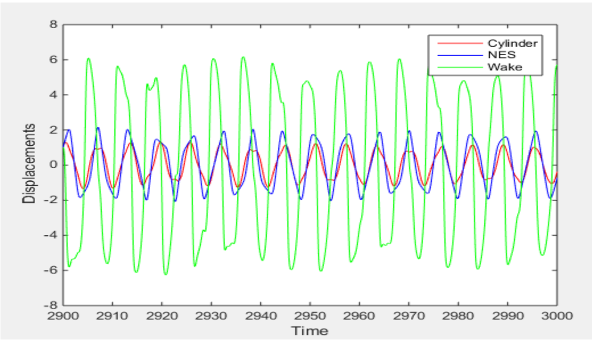

Fig.8- Time domain (Eq^{n}2)

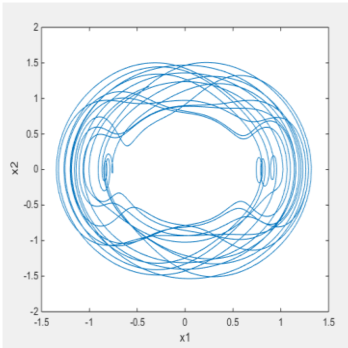

Fig.9- Phase portrait (Eq^{n}2)

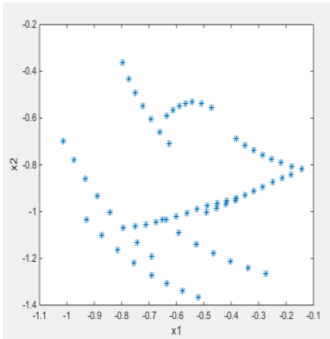

Fig.10- Poincare section (Eq^{n}2)

Table 1: Effect of mass ratio on the response of the system

Mass ratio	Cylinder amplitude (Y_2)		NES amplitude(Y_1)	
0.01	0.38	0.18	0.6	0.35
0.02	0.3	0.005	0.4	0.025
0.25	-	1	-	2

2.2.2 Effect of damping of NES

Now we discuss the effect of damping on the performance of NES.

When damping of NES is *Cnes* = 0.4 *C* it is observed that cylinder amplitude is *Y2* = 0.25 and NES amplitude of *Y1* = 0.45 which is better than Nayfeh model (Eqn.1) whereas from Nayfeh model (Eqn.1) *Y2* = 0.38 and *Y1* = 0.64. The amplitude of the cylinder is reduced to 75%. The system is showing a quasiperiodic response. This can be seen from phase portrait and Poincare section which is showing infinite points falling in circular form.

When damping is *Cnes* = 0.6 C it is observed that *Y2* = 0.2 and *Y1* = 0.4 whereas in Nayfeh model (Eqn.1) *Y2* = 0.38 and *Y1* = 0.66. Here amplitude of cylinder reduced to 80%. The system is still showing quasiperiodic response there is no qualitative change in response.

At *Cnes* = 0.8 *C* then we are getting *Y2* = 0.1 and *Y1* = 0.14. The system is showing still a quasiperiodic response. Amplitude reduced to 90%.

C_{nes} **= 0.4C:**

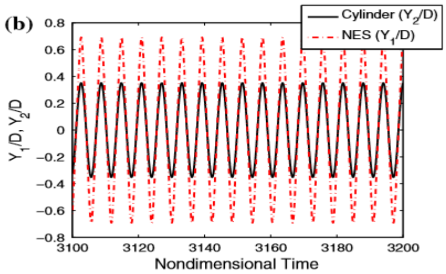

Fig.11- Time domain (Eqn1)

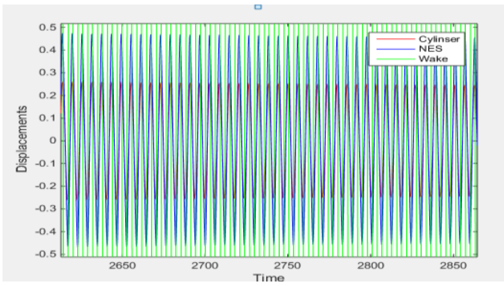

Fig.12- Time domain (Eqn2)

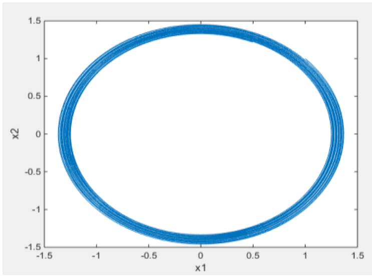

Fig.13- Phase portrait (Eqn2)

C_{nes} **= 0.6C:**

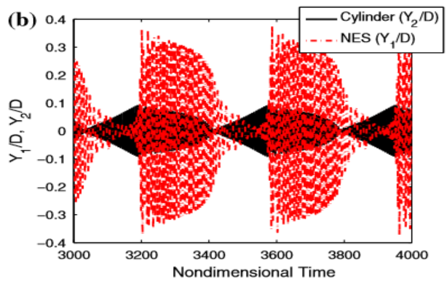

Fig.14- Time domain (Eqn1)

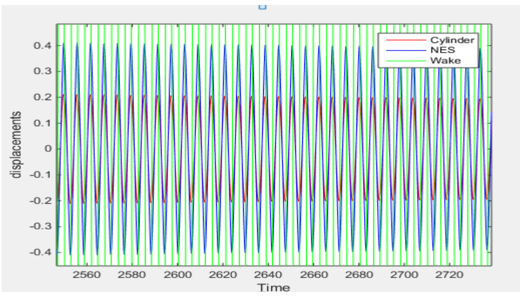

Fig.15- Time domain (Eqn2)

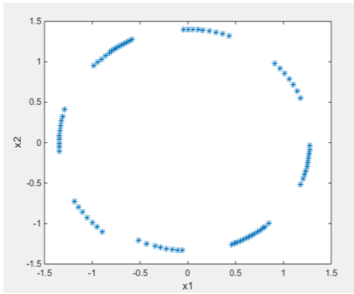

Fig.16- Poincare section (Eqn2)

C_{nes} **= 0.8C:**

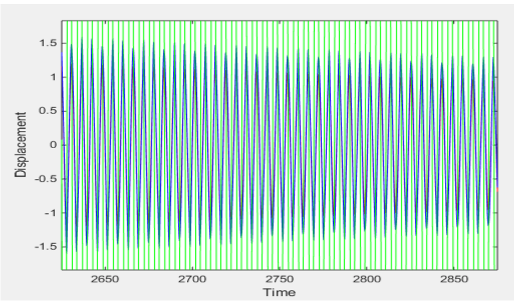

Fig.17- Time domain (Eqn2)

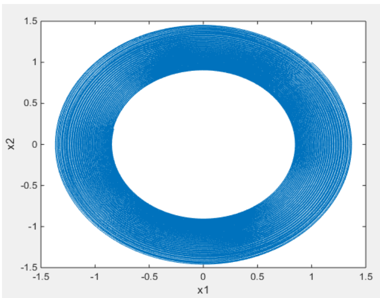

Fig.18- Phase portrait (Eqn2)

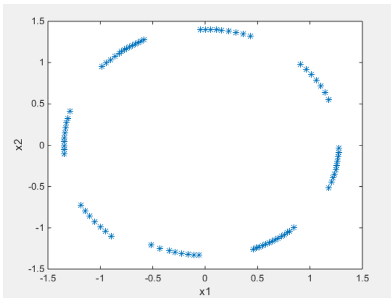

Fig.19- Poincare section (Eqn2)

Table 2: Effect of NES damping on the response of the system

NES damping	Cylinder amplitude (Y_2)	NES amplitude(Y_1)
C_{nes} = 0.4C	0.25	0.45
C_{nes} = 0.6C	0.21	0.41
C_{nes} = 0.8C	0.1	0.14

2.2.3 Effect of coupling

Considering the effect of coupling parameters on the response of the system is very important. As force acting on the cylinder by the wake (M) and force acting on the wake by the cylinder (F) are the strongly coupled parameters in the system.

If we consider the effect of *M* as the *M*=0.0002 system is showing quasiperiodic response with an amplitude of $Y2$ = 0.1 and $Y1$ = 1.5. Suddenly system going to unstable focus response as we change *M* = 0.02 and amplitude of cylinder and NES grows continuously. This is very dangerous to the system so we have to avoid M is high. It should be as small as possible.
If we consider the effect of *A* as *A* = 0 system is showing multiple frequency response with the same RMS amplitude as in effect of parameter *M* and can be seen from the frequency domain. The system is showing quasiperiodic response with the same RMS amplitude of cylinder and NES when *A* = 12. So *A* should be high as possible to overcome the force coming from the wake.

M = 0.0002:

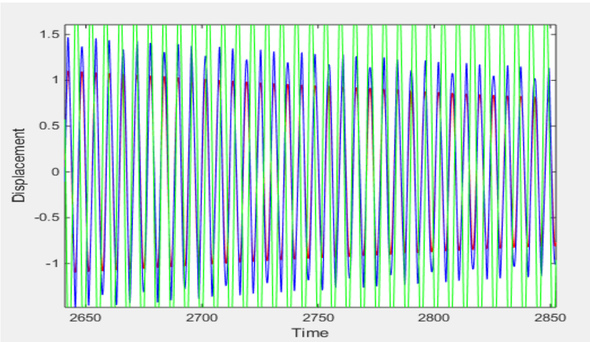

Fig.17- Time domain (Eq^{n}2)

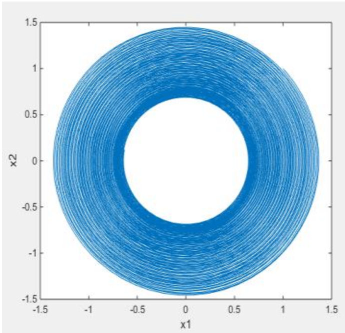

Fig.18- Phase portrait (Eq^{n}2)

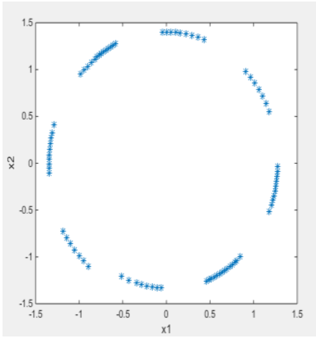

Fig.19- Poincare section (Eq^{n}2)

M = 0.02:

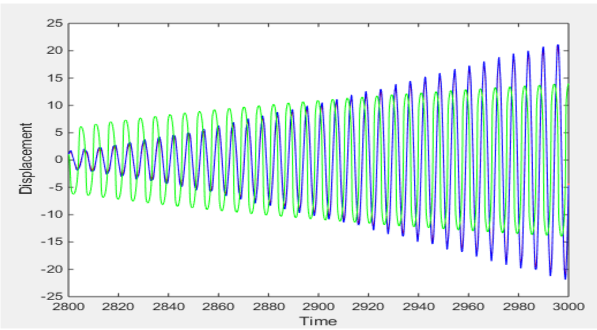

Fig.20- Time domain (Eq^{n}2)

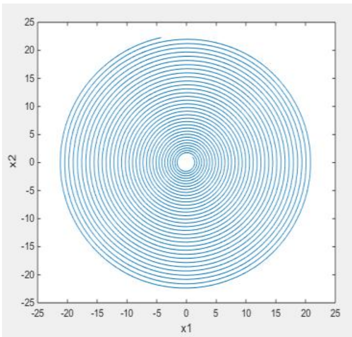

Fig.21- Phase portrait (Eq^{n}2)

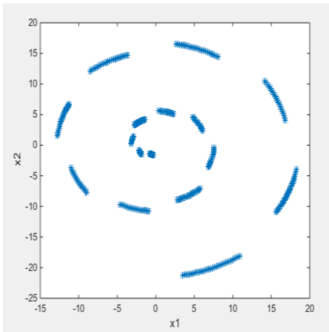

Fig.22-Poincare section (Eq^{n}2)

3. CONCLUSION

We have investigated and studied in detail the feasibility of using the NES to control the flow induced vibration and analyzed stability of system. We have solved the governing equations using computer software. There is a critical mass ratio at which NES unable to control the FIV. Minimum NES damping is required and coupling parameters should be small.

REFERANCES

1) Blevins, R.D., 1990. "Flow-Induced Vibrations." Van Nostrand Reinhold, New York.

2) Gabbai, R.D., Benaroya, 2005. "An overview of modeling and experiments of vortex-induced vibration of circular cylinders." Journal of Sound and Vibration. 282 (575-616)

3) M.L. Facchinetti, 2002. "Coupling of structure and wake oscillator in vortex induced vibrations." Journal of Fluids and Structures 19 (123-140).

4) Facchinetti, M.L., de Langre, E., Biolley, F., 2001. Vortex-induced waves along cables. Bulletin of the American Physical Society 46 (128).

5) Ali H. Nayfeh, 2014. "Effects of nonlinear energy sink on vortex induced vibration." Nonlinear Dynamics 77 (667–680)

6) Bearman, P.W. 1984 "Vortex shedding from oscillating bluff bodies". Annu. Rev. Fluid Mechanics 16 (195–222)

7) Williamson, C.H.K. 1996 "Vortex dynamics in the cylinder wake". Annual review of Fluid Dynamics 28 (477-539)

8) S.S. Chain, 1987 "Flow Induced Vibration of Cylindrical Structure". Hemisphere Publishing Corporation, New York.

9) Tumkur, R.K.R., Calderer, R., Masud, A., Bergman, L.A., Pearlstein, A.J., Vakakis, A.F., 2011: "Passive suppression of laminar vortex induced vibration of a circular cylinder". ENOC 2011, Rome, Italy.

10) Malatkar, Nayfeh, 2007: "Steady-state dynamics of a linear structure weakly coupled to an essentially nonlinear oscillator". Nonlinear Dynamics 47 (167–179).