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The Simulation of A Piezoelectricity Energy Harvesting Structure from Vortex Induced Vibration*

Li Li, Jinliang Wang, Zhanling Ge
College of Computer Science and Technology
Shenyang University of Chemical Technology
Shenyang, China
lily_jilin@163.com

Chuanxin Gu
Laboratory of Sensor Technology
Beijing Information Science & Technology University
Beijing, China

Li Li, Hongquan Liang
Science and Technology on Communication Networks
Laboratory, The 54th Research Institute of China
Electronics Technology Group Corporation
Shijiazhuang, China

Abstract—**A new structure of energy harvesting is proposed. In the structure, the bimorph piezoelectric cantilever is inside the flexible circular tube, the circular tube stands in the fluid, the axial direction is perpendicular to the incoming flow direction, and the neutral plane of the cantilever beam in the cylinder is parallel to the flow direction. The cyclical vibration of the flexible tube caused by the flow-induced vibration drives the piezoelectric cantilever inside the tube to vibrate and generate electric energy. The effect of bluff body to the vibration of structure was investigated using FSI(fluid structure interaction) simulation. The results showed that the vibration of harvesting structure was more stable when a rigid cylinder was in front of the structure as a bluff body than a flexible cylinder. The simulation of three flexible tubes standing in a line and a rigid cylinder as a bluff body was performed, in order to find the optimal position for placing the flexible tube behind the bluff body. The simulation results showed that the second flexible tube behind the bluff body has an optimal and stable vibration response. The relationship between the fluid velocity and the vibration of structure was researched using the simulation method. The results showed the optimal vibration state occurred when the fluid velocity was 1.1m/s and the radius of the tubes was 10mm. Furthermore, piezoelectric coupling simulation and energy harvesting circuit simulation were carried out. The voltage distribution and the voltage with time were obtained. The voltage response was 85V, 9Hz AC when the harvesting structure was in optimal vibration state. Finally, the LTC3588 chip was used to simulate the energy harvesting circuit, and the simulation results show the energy harvester can meet the practical requirements.**

Keywords—Energy harvesting; Piezoelectric material; Vortex-induced vibrations; FIS; Simulation; ADINA;

I. INTRODUCTION

Ocean is a new groping territory to human beings, vortex induce vibration (VIV) is a common phenomenon in ocean environment. When the viscous fluid flows past a cylinder and Reynolds number (Re) meets certain conditions, the fluid generates boundary separation, and the asymmetrical vortexes occur at the back of the cylinder in fluid, as shown in Figure1(a). When the frequency of vortex shedding is equal to the natural frequency of the cylinder, the unstable asymmetrical vortexes become the stable, asymmetrical, regular, opposite direction of rotation, alternate shedding vortexes. Because of the sudden and strongly destructive of vortex induced vibration, it is seen as a harmful phenomenon in many territories all the time. There are numerous studies about mechanism of vortex induced vibration and methods of controlling it. Bokaian and Geoola[1] studied the problem of vortex induced vibration of a double cylinder system, experiments showed that the vortex induced by vibration was strongly related to the Reynolds number and turbulent characteristics of free flow. Brika and Laneville[2] conducted a systematic double-cylinder dynamic coupling experimental study. The results showed that there were intermittent and hysteresis phenomenon in the vibration response.

However, it appears some theoretical reports and experimental results about generating electricity by vortex induced vibration recent years. The earliest researches are energy harvesting EEL by Allen and Smith[3] and Taylor[4], The best-known is VIVAC (the Vortex Induced Vibration for Aquatic Clean Energy) by marine renewable energy lab in university of Michigan[5,6].

Using the piezoelectric materials for power generation is a hot research topic at present. The piezoelectric materials have many advantages, such as simple structure, no electromagnetic interference, no pollution, amenable miniaturization and long life. Consequently, it has wide practical value and application prospect in power supply.

At present, several kinds of the piezoelectric energy harvesting structure from vortex induced vibration have been proposed. In addition to EEL, several rigid tube structures supported piezoelectric beam were researched by Abdelkefi[7] and Erik[8] etc. The elastic support of the long thin-walled piezoelectric tube piezoelectric structure that was proposed by Xie[9] et al. A new of structure of piezoelectricity energy harvesting from vortex induced vibration is presented in this paper.

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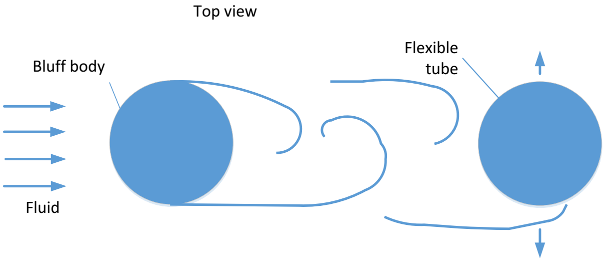
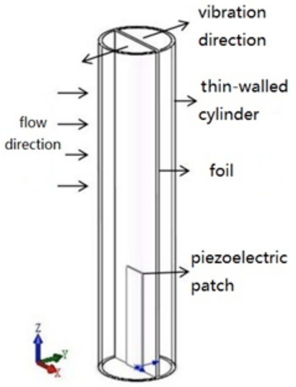
II. STRUCTURE

The new structure of piezoelectricity energy harvesting from vortex induce vibration was put forward for power supply to nodes of underwater wireless sensor network. It consists of a thin-wall flexible cylinder with built-in piezoelectric cantilever beam. As shown in the Figure 1(b).

The vortexes are shedding alternately at the back of the bluff body when the fluid flows around a bluff body. The structure behind is able to vibrate periodically by the actuation fluent vortexes, and then it drives flexural vibration of piezoelectricity cantilever to product electric energy. Piezoelectricity cantilever is inside of the cylinder, and isolates from external fluid, which could not only more prone to coupling resonance, but also avoid great fatigue damage and corrosion of piezoelectricity cantilever.



(a) Vortex induced vibration



(b) The structure

Fig. 1. The prototype of piezoelectricity energy harvesting structure from VIV

III. SIMULATION ANALYSIS USING FSI

Computer simulation of FSI is able to reveal accurately the motion state and characters of the interaction of fluid and structure before the physical experiments. So several groups of FSI simulation were carried out in order to analyze the impact of the bluff on the vibration of structure. The bluff body and energy harvesting structure both are flexible tubes in the first group. The bluff body is a rigid cylinder and the structure is a flexible tube in the second group. The array composed of three structures was investigated in the third group.

A. Settings of Parameters and Conditions in simulation

In the FSI simulation, fluid region is a cuboid. The inlet velocity of fluid is 1.1m/s. The bluff body and structure are respectively a rigid cylinders and a flexible circular tube. The specific calculation parameters are shown in Table I.

B. The influence of bluff body on vibration state of structure

The results of first two groups simulation experiments were gotten and compared after the following process which includes setting control parameters, modeling and meshing of fluid domain and solid domain, simulation and aftertreatment. The mesh model of fluid and structures is shown separately in the figure 2 and 3. The bluff body is respectively a flexible circular tube and a rigid cylinder in the figure 3(a) and (b). The bluff body is upstream of the fluid field.

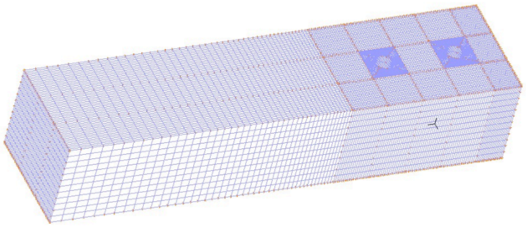
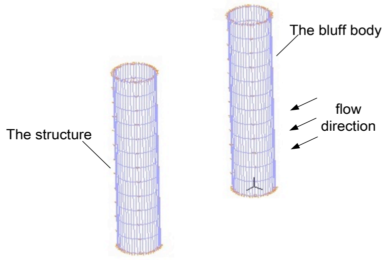


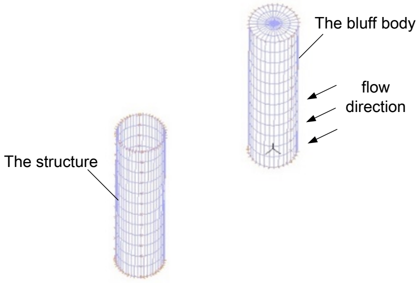
Fig. 2. Three-dimensional geometric model of fluid domain

TABLE I. THE RELATED PARAMETERS OF ENERGY HARVESTING STRUCTURE IN SIMULATION

Material	Characteristic parameter	symbol	unit	numerical value	Material parameter	symbol	unit	numerical value
Fluid field	length	a	mm	510	density	ρ	kg/m^3	1000
	width	b	mm	120	viscosity	η	Pa/s	0.001
	height	h	mm	100	velocity	v	m/s	1.10
Rigid cylinder	radius	r	mm	10	Young modulus	E	Pa	2.02×10^{11}
					Poisson ratio	μ	-	0.3
	height	h	mm	100	density	ρ	kg/m^3	7800
Flexible circular tube	radius	r	mm	10	Young modulus	E	Pa	17800000
	height	h	mm	100	Poisson ratio	μ	-	0.47
	thickness	δ	mm	2	density	ρ	kg/m^3	1600

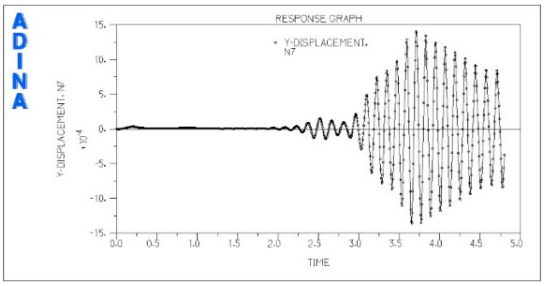


(a) The bluff body is flexible

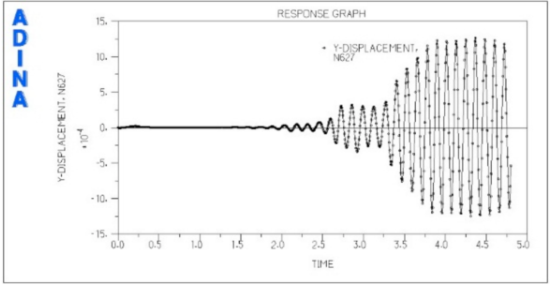


(b) The bluff body is rigid
Fig. 3. The mesh model of solid region

It can get the simulation results according to FSI calculation. The vibration response curves of the flexible structure in two simulation groups are shown in the figure 4.



(a) The first group



(b) The second group
Fig. 4. Vibration response curves of flexible structure

Comparing figure 4 (a) and (b), the flexible structure started vibrating at the same time in two groups. The starting time are both the third second. The largest deformation in the first group is 14×10^{-4}m and greater than that being 12×10^{-4}m in the second group. However, we can see that the vibration state in the second group is more stable than that in the first one. And in practical energy harvesting applications, the stability of the power supply is very important. We think the rigid bluff body is better than the flexible one for the energy harvesting structure.

C. *FSI Simulation for energy harvesting structure array*

In order to get the best vibration response position behind the bluff body, we simulated the array composed of three flexible structure standing in a line behind a rigid bluff body in water. The characteristic and material parameters of fluid domain and solid domain are same to that in the previous groups. The distance between each two tubes all is 0.08m. The model of structure array are shown in Figure 5.

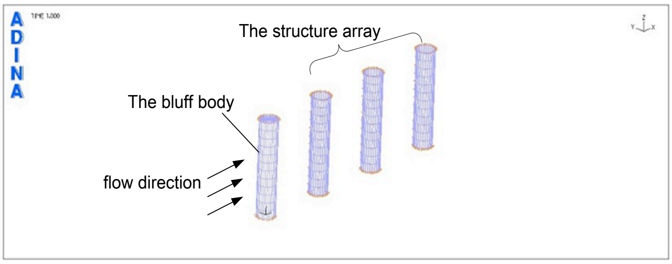


Fig. 5. Mesh model of the structure array

We can get the following simulation results after FSI simulating calculation.

a) Fluid field pressure distribution cloud chart

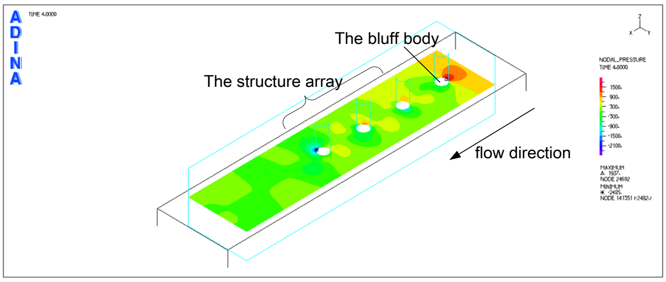
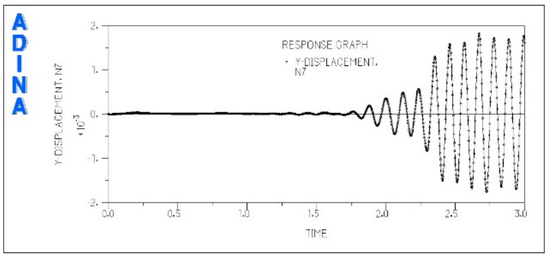


Fig. 6. Pressure distribution cloud map of fluid region

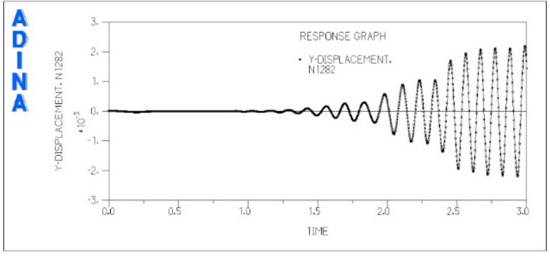
It is shown in the figure 6 that fluid region pressure distribution cloud map of XY-section. We can clearly know from the figure that the alternate eddies are emerging and shedding after fluid flows through the first bluff cylinder. Flexible cylinder became deformed because of eddies. Figure 6 proved also that the vibration of structure array was taking place driven by fluid flows.

b) The deformation of flexible structure

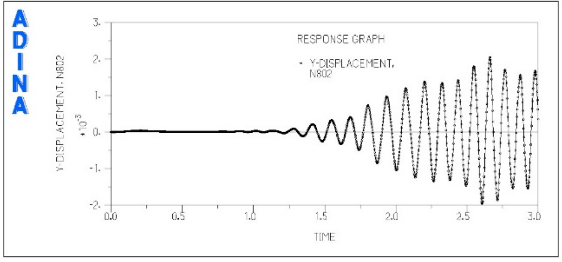
We got the stress and deformation cloud map of the structure array after processing solid solution file. It is similar to the pressure distribution map of fluid region. To observe the deformation of flexible cylinder in detail, we select a monitoring point on the top of tube. The amplitude response of the top of the three tubes is shown in the figure 7.



(a) The first tube



(b) The second tube



(c) The third tube

Fig.7. Time-amplitude curves of the top of flexible tubes

As we can see from the figures, under the combined action of a bluff body and the structure array, the amplitudes of the three flexible circular tubes are respectively 1.85 $\times 10^{-3}$m, 2.3 $\times 10^{-3}$m, 2.2 $\times 10^{-3}$m. The difference was small in three tubes. We can also observe the vibration of second tube is more stable than that of the first and third tubes.

The second tube begin to vibrate at 1.0s, the amplitude of vibration increasing gradually, and law of vibration begin to stabilize at 2.5s. The peak amplitude is 2×10^{-3}m, the frequency of oscillation is approximately 9Hz.

c) The influence of fluid velocity on the vibration of structure array

We carried out several groups of simulation in order to investigate the influence of fluid velocity on the vibration of structure array. We got multiple sets of simulation data by changing the fluid velocity (0.55m/s-1.15m/s). The vibrational state of cylinder array all are analogous in these groups of simulation. We select a monitoring point on the upper and middle part of cylinder respectively, and the various amplitude of these points with the fluid velocity is shown in the figure 8.

The amplitude of vibration response of the flexible structure was increasing first and then decreasing with the increase of the fluid velocity. On the whole, the vibration amplitude of the upper part is bigger than the middle part in a structure. We can see the biggest amplitude response appears on the upper part of the second tube when the fluid velocity reaches 1.1m/s. The deformation trend in this article is same as that of Khalaka and Wiliamson[10].

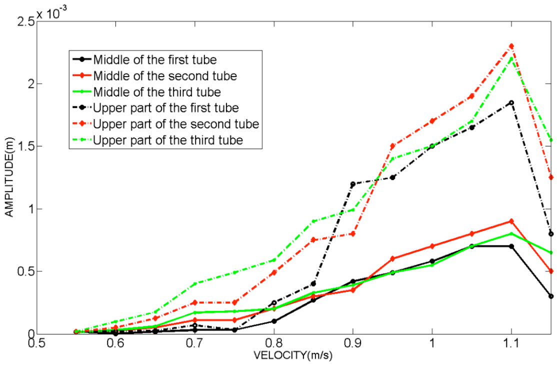


Fig. 8. The curve of vibration amplitude with the fluid velocity

IV. THE ANALYSIS OF THE OUTPUT VOLTAGE USING ELECTROMECHANICAL COUPLING SIMULATION

A thin bimorph piezoelectric cantilever is inside of the flexible tube in our energy harvester. One side of the cantilever fixes, the other side of cantilever is forced to bend with the vibration of flexible tube. We simulated the electromechanical transformation process of cantilever by forcing load and observed the voltage distribution of the piezoelectric plates.

A. piezoelectric coupling simulation

We got the voltage distribution of piezoelectric cantilever and showed in figure 9 through these processes, such as setting up material parameters (shown in Table II), modeling piezoelectric cantilever, meshing, applying load, solving and post processing.

It was found in the figure 9 that the deformation on the root of the piezoelectric cantilever is bigger than others, so its voltage is also bigger. The ladder-like distribution was found in voltage cloud figure clearly.

The secondary development of piezoelectric simulation in ADINA was conducted by python language in order to investigate the various voltage of piezoelectric cantilever with the vibration of structure. Combined with the Python language, the computer can complete the calculation automatically for multiple data on the piezoelectric simulation, and draw the piezoelectric response curve shown in figure 10.

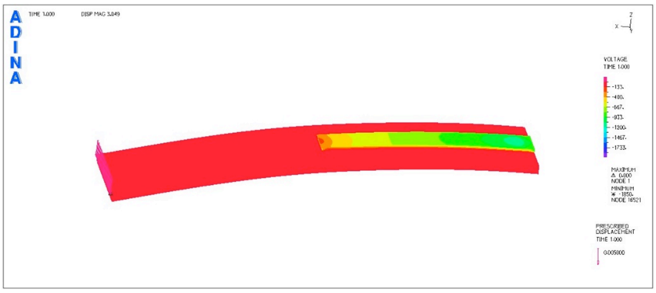


Fig. 9. The voltage distribution of piezoelectric cantilever

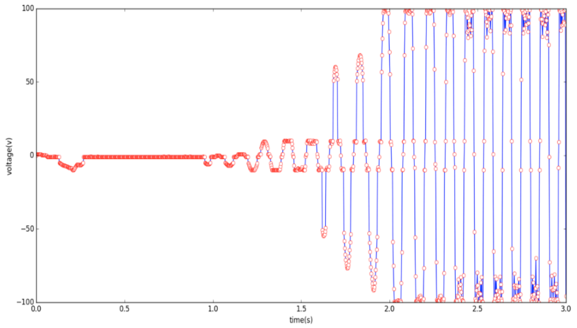


Fig. 10. The voltage response curve of piezoelectric cantilever

It can be seen from the figure10 that the voltage variation law became stable at 2s, and it could be roughly considered as a trigonometric curves, its frequency was 9Hz, amplitude was 85V. It can be used as a voltage input in the next section of the energy harvesting circuit design.

B. energy harvesting circuit

The input of energy harvesting circuit is voltage power according to the previous simulation. Energy harvesting circuit using LTC3588[11] as the main chip.

TABLE II. THE PARAMETERS OF PIEZOELECTRIC CANTILEVER

material	material properties		unit	material parameters
piezoelectric plates		length	mm	50
	structure size	width	mm	10
		thickness	mm	0.5
	Elastic Modulus		N/m^2	2.0×10^9
	Poisson's ratio		-	0.29
	Shear modulus		N/m^2	0.775×10^9
	Piezoelectric strain coefficient d_{31}		C/N	2.2×10^{-11}
	Piezoelectric strain coefficient d_{32}		C/N	0.3×10^{-11}
	Piezoelectric strain coefficient d_{33}		C/N	-3.0×10^{-11}
	Dielectric constant		-	12
	Piezoelectric matrix		-	$\begin{bmatrix} 0 & 0.02876 & 0 \\ 0 & -0.05186 & 0 \\ 0 & -0.0007014 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$
opper		length	mm	100
	structure size	width	mm	20
		thickness	mm	1
	Elastic Modulus		N/m^2	1.28×10^5
	Poisson's ratio		-	0.3
	density		Kg/m^3	8.4×10^3

According to the actual requirements, the design of the circuit shown in the figure 11.

We can see from the figure 11, PZ1 and PZ2 connected the positive and negative poles of the piezoelectric film respectively. The energy generated by the piezoelectric vibrations was stored in the capacitors C1 and C3 through the LTC3588. C1 and C3 from the storage capacitor into a discharge capacitor to charge the capacitor C2, when the voltage of C1 and C3 is higher than the limit voltage. At the same time the Pgood terminal went high, it means that the energy harvesting circuit is ready to power the transfer module and the stored power starts to be output from the out. C1 and C3 were converted from discharge capacitors to charge capacitors, the Pgood goes low, the out stopped outputting power to the load resistors when the voltage of C1 and C3 is lower than the limit voltage[11].

We used the simulation software LTspice IV to simulate a specific energy harvesting circuit. It is based on the actual design parameters of the company and it is packaged in the software, the circuit can be more realistic simulation performance. The simulation graph is shown in Figure 12.

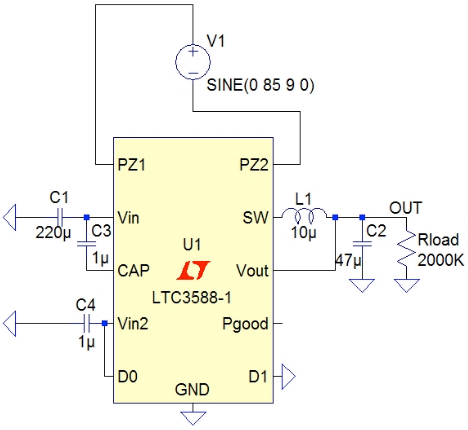


Fig. 11. Energy collection circuit diagram

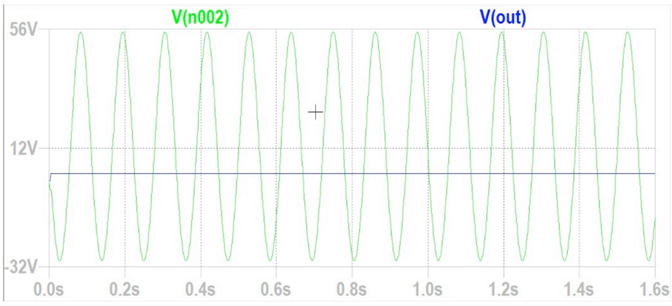


Fig. 12. Energy collection circuit simulation results

The green line in the figure is the alternating input voltage, its amplitude is 85V, and the frequency is 9Hz. But it shows a maximum voltage of 54.5V, a minimum of 30.5V and a symmetrical center of 12V in the figure 12. Because there is a boost circuit inside LTC3588, cause the overall AC voltage of the circuit to move up by 12V. The blue line is the output voltage, and the output voltage had been stable at 2.5V after 4.2ms.

V. CONCLUSION

A new type of energy harvesting structure is proposed. Fluid-solid coupling simulation was carried out in ADINA, and the simulation experiments showed that the second flexible tube behind the rigid bluff body had the best vibration response. The vibration response curve of the flexible tube was obtained with changing the water flow velocity. The correctness of the fluid-solid coupling is verified.

The voltage distribution of the piezoelectric cantilever is obtained by applying a deformation to the free end of the cantilever beam. At the same time, the secondary development of piezoelectric simulation was carried out, and alternating current was got eventually. The frequency is 9Hz, and the amplitude is approximately 85V. The output voltage had been stable at 2.5V through the energy harvesting circuit.

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