SAW Sensors for Measurement of Surface Forces in Fluid Flows

(유체흐름에 의한 표면력 측정을 위한 탄성 표면파 센서)

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ABSTRACT

The determination of fluctuating normal and shear stresses on a structure embedded in a turbulent flow is an important problem in fluid dynamics. A new surface acoustic wave (SAW) sensor is developed to detect the surface forces(wall pressure and wall friction) and the direction of the flow as a function of position and time on the structurce. The sensor is composed of a pair of SAWs having an identical center frequency with surfae waves experiencing shear stresses in opposite directions. The difference in SAW velocity is proportional to the shear stress associated with the flow. The difference between the mean velocity of a pair of the SAWs subject to the flow and the velocity of the SAW in a stationary fluid is proportional to the pressure (normal stress of the flow). The direction of fluid flow is determined through an arrangement of three pairs of SAW sensors in a manner similar to a strain rosette. The SAW sensor can operate over a wide frequency range. Thus, by employing an appropriate center frequency depending on the spatial and temporal resolution required, we can simultaneously measure the fluctuating surface forces and the direction of laminar and turbulent flows both locally and globally.

요 약

유체 동역학에서, 난류에 의해 수중 구조물에 가해지는 압력과 전단력의 측정은 중요한 문제이다. 이러한 유체의 흐름에 의한 압력과 전단력, 나아가 유체의 흐름방향까지 시간과 거리의 함수로 측정할 수 있는 새로운 탄성표면파 센서가 개발되었다. 센서는 압축, 안장형 전단력올 받는 두개의 표면파로 구성이 되었으며, 이 두 파동의 전파 속도차는 유체에 의해 가해지는 전단력에 비례한다. 정지류 속의 표면파와 흐르는 유체 속의 표면파의 속도차는 또한 유체흐름에 의해 가해지는 압력에 비례한다. 이 센서를 응력 로젯과 같이 배열하면 유체의 진행방향도 함께 측정할 수 있다. 표면파 센서는 넓은 주파수 대역에 걸쳐 사용이 가능하므로, 적절히 설계하면 유체의 흐름에 의한 표면력과 유체의 진행방향을 동시에 거리와 시간의 함수로서 국부적으로, 광역적으로 측정할 수 있다.

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I. INTRODUCTION

Turbulent flow describes a situation where the stress and velocity at a point fluctuate in a random fashion with time about mean values. Whose motion is unpredictable and at the present time its complex flow mechanism is not fully understood, despite its great importance[1]. Therefore, the determination of unsteady surface forces (wall pressure and wall friction) on a structure embedded in a turbulent flow has been an important problem in fluid dynamics. This is because the information about the surface forces may lead to a better interpretation and description of complex flow fields, identification and delay of the transition point from laminar to turbulent flow and, ultimately, the cancellation of the rtubulence mechanism around the surface of a structrue. Much theoretical and experimental work has been done to develop a good measuring technique for space and time dependent surface forces in a fluid flow. So far, surface forces have been measured by various devices such as the Preston tube, the Stanton tube, a sublayer fence, a hot-film anemometer and floating element sensors[1, 2, 3]. But no really satisfactory direct measurement methods are available yet.

A surface acoustic wave (SAW) is very sensitive to its environment. Here, the environment encompasses any variable surrounding the SAW, such as temperature, humidity and forces. When a SAW is exposed to these variables, it shows a great deal of velocity change in measure with the variable changing. If the environment is a laminar or turbulent fluid flow, the SAW can respond to the changing normal and shear stresses associated with the flow. The design techniques for SAW sensors have been under intensive worldwide investigation for the past several decades and are well developedfor some application. With these techniques, and throrugh the study of surface waves and the effect of laminar and turbulent flows on the SAW propagation, new SAW sensors are developed which can overcome the limitations found in the conventional measurement devices. Compared with current measurement instruments, the new SAW sensors offer several attractions : First of all, with one sensor, time and space dependent normal and shear stresses as well as flow direction can be measured simultaneously without requring a prior knowledge of the flow field. The sensing area can be easily controlled by employing various center frequencies of the SAW. A large (global) sensor of low frequency can measure globally averaged surface forces over a long distance and a small (local) sensor of high frequency can measure detailed local surface forces over a short distance. As proved in other applications, such as temperature and humidity measurement[4], these sensors exhibit a very good sensitivity. The sensor can be glued directly to any surface without disturbing the body shape like plug-in probes or disturbing the flow field like intrusive devices. Restrictions concerning the surface geometry of the sensor and structures are largely eliminated. Therefore, the SAW sensors are promising new devices that accurately document the unsteady wall pressure and wall friction development as a function of both time and space.

II. Concept of New SAW Sensors for Measurement of Surface Forces in Fluid Flows

In Fig. 1, there are three SAW sensors composed of a piezoelectric layer, a substrate and interdigital transducers (IDTs). All the three sensors are identical including materials, IDTs and a center frequency. To the sensor A, no fluctuating surface force is applied. It is as if immersed in a stationary water. Everything is stable and the SAW velocity V_0 of this sensor is used as a reference. The other two sensors B and C are put under laminar or turbulent flow and the SAW experiences both normal pressure P and shear stress S given by the flow. The magnitude of the P and S for the two sensors is the same. But in the sensor B, the right end of the piezoelectric layer is fixed and in the sensor C, the left end is fixed. In the two sensors, B and C, the application of the normal pressure P has the same effect on both of the sensors. But the shear stress S to the two sensors will deform the layers of the sensors in opposite directions. The layer suface of the sensor B will be compressed, while that of the sensor C expanded[5]. What the SAW experiences in the sensor B is named compressive shear stress and, in the sensor C, tensile shear stress. Then in the sensor B, the velocity of the SAW increases to $V_1+\Delta V_1$, and in the sensor C, the velocity decreases to $V_1-\Delta V_1$[6]. The common velocity V_1 of the two sensors is

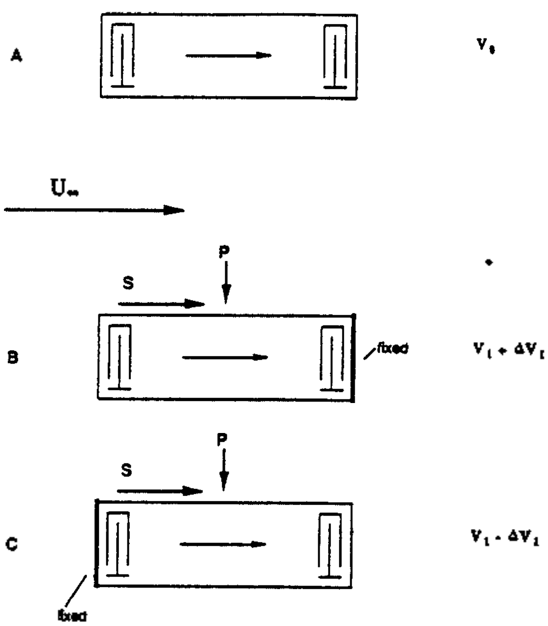

Fig. 1. Concept of new SAW sensors for measurement of surface forces in fluid flows.

given by the normal pressure and the difference between them $2\Delta V_1$ is given by the shear stress. Thus in practice, the difference between the average velocity of the sensors B & C and the sensor A is given solely by the effect of normal pressure. The velocity difference between the sensors B and C is given solely by the effect of the shear stress because the normal pressure for both of them is the same. Hence from the SAW velocities of the three sensors in Fig. 1, we can

$$\frac{(V_1+\Delta V_1)+(V_1-\Delta V_1)}{2}-V_0 = V_1-V_0 = \Delta V \propto P$$

$$(V_1+\Delta V_1)-(V_1-\Delta V_1) = 2\Delta V_1 \propto S \qquad (1)$$

set up the following equations.

Ⅲ. Design of a SAW Sensor

The concept of the SAW sensors for measurement of wall shear stress in laminar and turbulent flows is verified through experiments under both static and dynamic loading conditions. For the experiments, two low frequency SAW sensors are designed. They are composed of a PVDF film, a plexiglass substrate and silver electrodes. The SAW is propagating in the stretched direction of the PVDF film. For measurement, the SAW sensors have to be imersed in a liquid and the technique developed in Ref. 7 is used for the design. In the design, for the material properties of PVDF, recently measured data[8] are used.

Based on calculation results for the design, two low frequency SAW sensors are made, one for a static experiment and the other for a dynamic experiment. A 0.53 mm thick PVDF film is attached to a plexiglass substrate with epoxy. After curing for eight hours, electrodes are drawn with silver paint. Each electrode has 10 fingers. The center frequency of the sensors is 702 KHz in air.

Ⅳ. Static Experiment

4.1 Pressure measurement

In the static pressure measurement, the sensor is immersed in a tank filled with motor oil (density=0.6) and the pressure applied to the delay line (surface of the piezoelectric layer) is controlled by changing the depth of the oil in the tank. The reason motor oil has to be used instead of water is to insulate the electrodes. But later, the electrodes are insulated with a Rho-C rubber coating. The test equipment consists of a LeCroy 9400 A digital oscilloscope, a Panametrics pulse generator 5055PR and a Krohn-Hite 3202 filetr. The oscilloscope can perform the FFT operations. Figure 2 is a schematic of the experimental setup. All the measurements are made at room temperature. Figure 3 shows the typical wave form generated by the sensor. The main signal in the filgure is the Rayleigh waves and the lower amplitude signals are thought to be reflected transverse bulk waves and Love waves. Even though the SAW suffers attenuation in propagation, the main signal is clear. SAW velocity in a homogeneous nonpiezoelectric material is affected by changes of boundary conditions at the surface, as well as density and stiffness of the medium. In piezoelectric materials, the velocity is affected by changes of electrical conductivity as well, since that alters piezoelectric stiffening. In this section, the change of the static pressure proportional to the depth of the oil causes a change of the SAW velocity. The velocity change is measured in terms of a phase shift.

Measurement results are shown in Fig. 4. As seen in the figure, there is a linear relationship

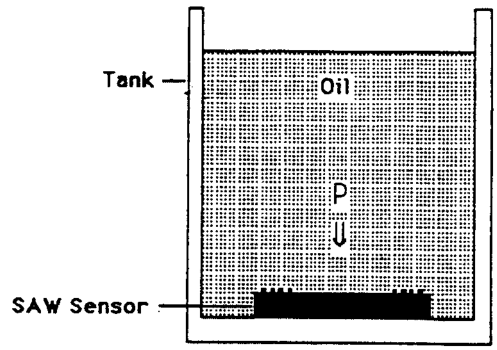

Fig. 2. Experimental setup for normal pressure measurement

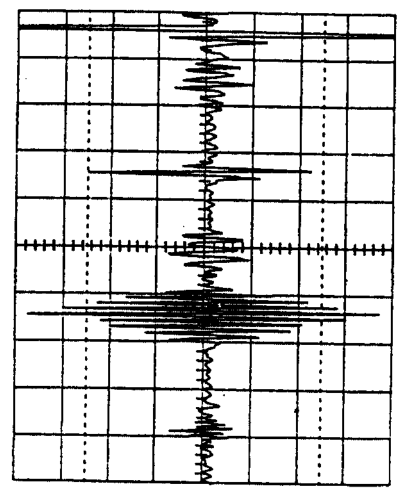
Fig. 3. Typical wave form the SAW sensor

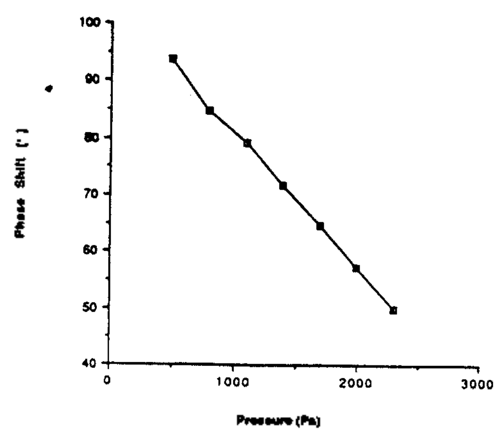

Fig. 4. Phase shift and pressure variation from the measurement with the SAW sensor.

between the two variables, pressure and phase shift. The sensitivity is 1.5° of phase shift per 1 cm change of oil depth. This value equals 1.5° phase shift for 60 Pa of pressure change. Because the phase shift can be measured accurately to 0.1°, the sensor can sense the pressure changes accurate to 4 Pa. If converted into a length scale, the pressure sensor can detect a change in oil depth of the order of 0.67 mm (for water up to 0.4mm). But the sensitivity is not of so much concern at the present time. If a longer delay line is used, and frequency shift is measured instead of the phase shift by constructing an oscillator circuit, the sensitivity could be much higher. The important accomplishment is the successful demonstration of an immersible SAW sensor and the observation of the linear relationship between pressure and phase shift. The predicted response of the SAW to normal pressure is confirmed experimentally.

4.2. Shear stress measurement

The same SAW sensor is exposed to shear stress. Figure 5 is the general view of the experiment. Because the magnitude of the shear stress to be tested is so small, big testing machines can not be used. Instead, a small box made of Rho-C Rubber is put on the delay line and by means of a roller, weights are applied, which result in the application of a shear stress on the delay line. In the measurement, two different cases are tried as described in Sec. 2, tensile and compressive shear stress application.

What happens to the piezoelectric layer of the two sensors is clearly shown in Fig. 6. In the two sensors, the layer is attached to the substrate with soft epoxy, and the right or left end of the layer is firmly fixed with a hard fixture. The magnitude of the normal stress(P) is the same and the application of the normal pressure P has the same effect on both of the sensors. But the shear stress S on the sensors A and B deforms the layer of the sensors in opposite directions. The layer surface of the sensor A is compressed, while that of the sensor B is expanded. With the application of shear stress, the SAW velocity change is measured in terms of a phase shift. All the measurements are made in the same manner as in the pressure measurement. Figure 7 shows the results of both the compressive and the tensile shear stress cases. The phases of the two sensors A and B start at

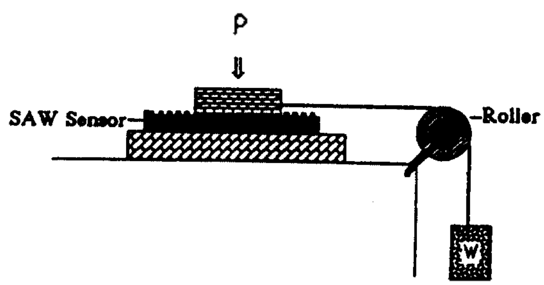

Fig. 5. Experimental setup for shear stress measurement

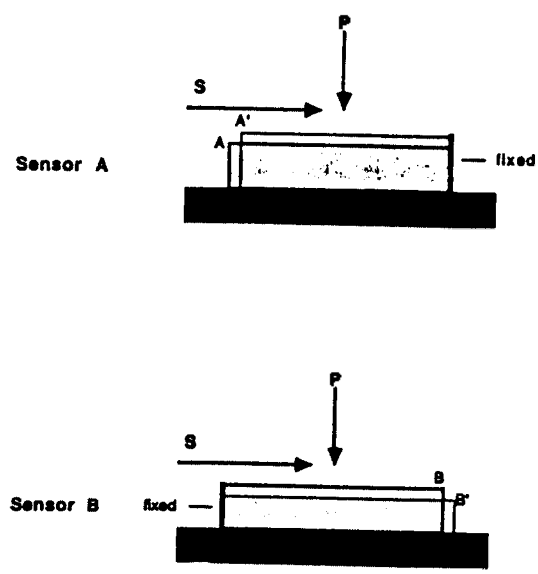

Fig. 6. The effect of compressive and tensile shear stress on the PVDF layer of the SAW sensor.

the same value because the normal pressure is the same for both of them. The phase shift of the SAW is proportional to the magnitude of the shear stress and the direction of the shift is opposite for the two types of shear stress. The amount of the velocity change is almost equal for the two cases. I n Fig. 8, the phase shift difference of the SAWs of the two sensors is proportional to the shear stress at the surface of the delay line. The addition of the compressive and tensile phase shift remains consant(0°) because the normal pressure is kept constant for both of the sensors. Therefore, the phase shift difference of the two sensors is solely due to the effect of the shear stress. Hence measurement of the phase shift difference of the two sensors shows the magnitude of the shear stress. In the measurement, 1° phase shift is obtained for 10 Pa of each type of shear stress.

Statically, the concept of the SAW sensor for the measurement of shear stress is proved.

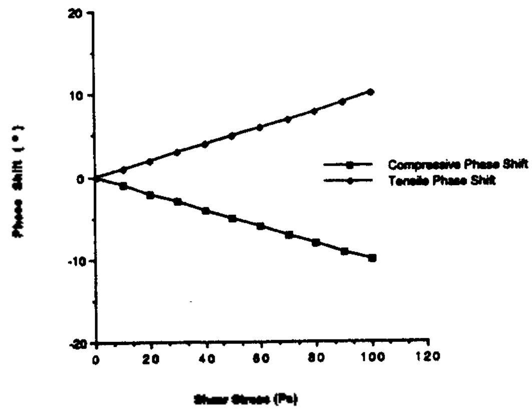

Fig. 7. Phase shift and shear stress variation from the measurements with the SAW sensor.

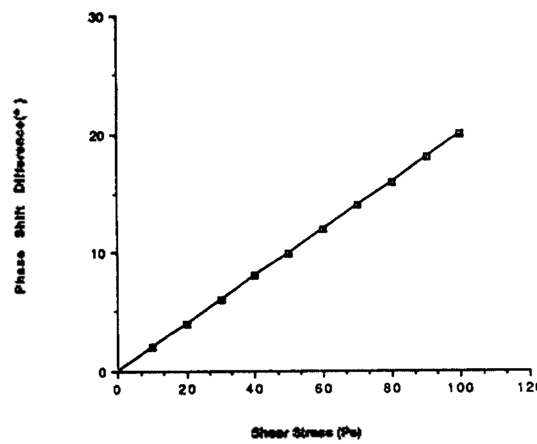

Fig. 8. Phase shift difference between the compressive and tensile shear stress sensor and shear stress variation.

V. Measurement of Normal Pressure and Shear Stress Associated with a Fully Developed Turbulent Channel Flow

For a dynamic experiment, a feedback oscillator circuit is composed with the SAW sensor. With a SAW delay line oscillator, the velocity change of the SAW in response to surface forces is measured in terms of frequency shifts instead of phase shifts.

The oscilltaor circuit is shown in Fig. 9. An electronic amplifier connects the output transducer to the input transducer so that oscillation results due to the positive feedback. The amplifier is Hewlett-Packard 461A, and the frequency counter is Hewlett- Packard 5300B.

The SAW sensor in the oscillator circuit is exposed to dynamic surface forecs generated by water flow. In a water tunnel (30cm×14cm× 732cm, width×depth× length), shown in Fig. 10, the SAW sensor is placed 559 cm from the front end of the tunnel. Water is made to circulate through the tunnel by an electric pump. The SAW sensor delay line is in contact with the water flow and the SAW continuously experiences normal pressure and shear stress given by the flow. For the insulation of the IDTs and electric wires, the sensor is coated with Rho-C rubber. The flow velocity is about 0.43 m/s. With the kinematic viscosity of water(1.013×10^{-6} m^2/s), the Reynolds number is calculated to be 2.4×10^6 at the point of measurement. Thus, the flow is a fully devel-oped turbulent flow. With the method suggested in Sec. 2, the resonant frequency of the SAW oscillator is measured. Measured data are shown in Table. 1.

When the SAW experiences tensile shear stress, the resonant frequency is about 750.3 KHz, and when the SAW suffers compressive shear stress, it is about 756 KHz. Difference of the frequency shifts is about 5.7 KHz. This difference is given solely by the effect of the shear stress applied by the water flow. The resonant frequency difference of 13.15 KHz, between the two situations when water is flowing and not, is totally due to the normal stress given by the flow. Therefore, the concept of the SAW sensors for the measurement of surface forces in laminar and turbulent flows is proved in dynamic conditions as well.

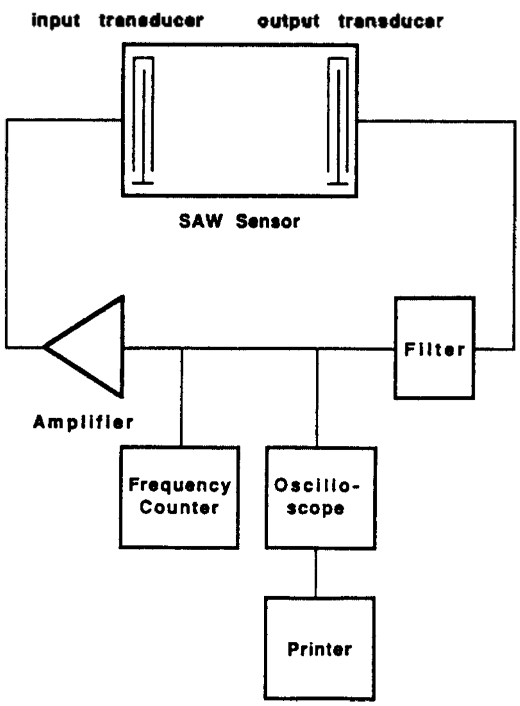

Fig. 9 Experimental setup for SAW oscillator sensor.

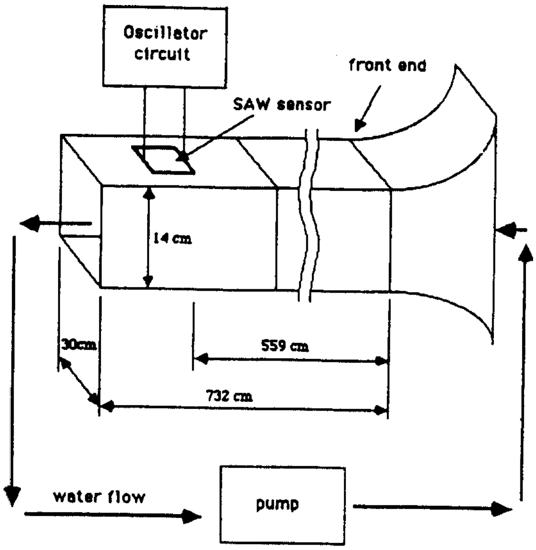

Fig. 10. SAW oscillator sensor in a water tunnel

Since the interpretation of wall shear stress is more inportant to the descripiton of flow fields, the performance of the SAW oscillator is investigated further for the measurement of wall shear stress applied by turbulent flow. To see how much shear stress is meant by 5.7 KHz frequency difference, the SAW oscillator is calibrated in the same manner as that in Sec. 4.2. The result of the calibration, shown in Fig. 11, indicates that the frequency difference of 5.7 KHz corresponds to the shear stress of 2.0 Pa. The oscillator circuit of Fig. 10 can measure the resonant frequency up to an order of 10 Hz. Hence, the shear stress can be measured accurately to 0.004 Pa. Compared with the phase shift measurement, the sensitivity of this frequency shift measurement is very high. The sensitivity can be improved further if a longer delay line and a higher resonant frequency are employed in the oscillator circuit.

In the measurement, resonant frequency of the sensor fluctuates with time. The temporal fluctu-ation of the resonant frequency differency for the two types of shear stress is measured and is shown in Fig. 12. In the figure, the fluctuating range is about 0.6 KHz. The fluctuation is natural because the shear stress itself applied by the turbulent flow is not constant but time varying. Measurement of the frequency difference with time, as shown in Fig. 12, leads to a documentation of the variation of the shear stress as a function of time. Spatial variation of the shear stress is also obtained if several sensors are located at different positions. But in the measurement, in addition to this time varying shear stress, several other factors may contribute to the fluctuation. The first is that the oscillator circuit may not be stable.

Generally, the stability is determined by a number of physical phenomena, including thermal and electronic noise, random temperature fluctuations, ambient noise, and changes in the transmission medium itself. More direct reasons are Johnson noise associated with the acoustic and transduction losses, and random phase changes in the amplifier.

A more acoustically stable environment and more electrically reliable equipment will solve this problem. The second is that the surface of the SAW sensor may not be perfectly smooth.

The rough edges of the sensor especially seem to contribute to the fluctuation. Use of a higher-level coating technique such as that in photolitho graphy [9] | and more careful handling of the sensor will remove this problem.

Table. 1. Resonant frequencies of the SAW oscillator sensor

state of the SAW sensor	resonant frequency (KHz)
in air	702.0
in stationary water	740.0
in water flow - tensile shear stress	750.3
in water flow - compressive shear stress	756.0

According to the calibration, the frequency shift difference of 5.7 KHz corresponded to a shear stress of 2.0 Pa. This value is a little larger than a general estimation[10]. There may be several reasons for this difference. Primary reason is an inaccuracy in the calibration of the SAW oscillator sensor. The calibration curve of Fig. 11 was obtained in a static condition while the measurement was done in a dynamic condition.

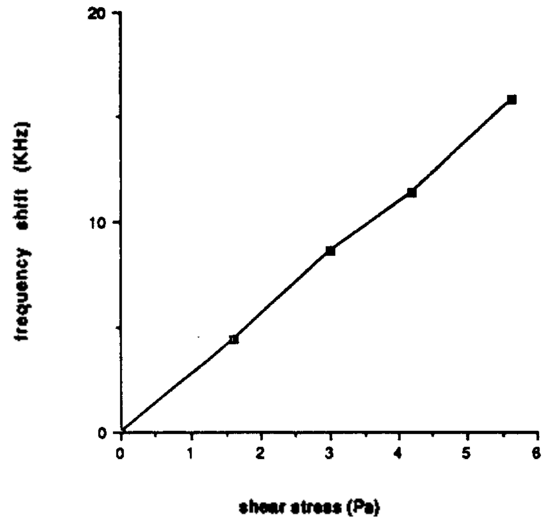

Fig. 11. Frequency shift difference between the compressive and tensile shear stress sensor and shear stress variation .

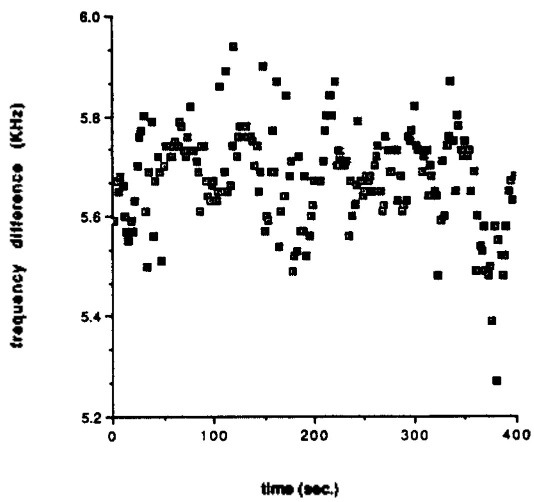

Fig. 12. Variation with time of the frequency shift difference due to the fluctuating skin friction associated with a fully developed turbulent channel flow.

Calibration of the SAW sensor under a dynamic loading condition will lead to a better interpretation of the SAW oscillating frequency shifts. Next reason is attr ibuted to experimental errors.

Measurement errors caused by a poor condition of the water tunnel is responsible for the difference of the two shear stress values.

Recording the measurement data in a better way like receiving the output from the frequency cou-nterwith a digital data acquisition system will also reduce the measurement errors.

Conclusively, the concept of the SAW sensor to measure the shear stress in laminar and turb-ulent flows described in Sec. 2 is proved in the dynamic test as well.

Ⅵ. Discussion

A turbulent fluid does not always flow one dimensionally. Its mean flow may be one dimen-sional. But, in general, its motion is characterized by a random behavior. Thus the method to sense the two-dimensional surface foces with the SAW sensors should be devised. In mechanics, with a strain rosette, we measure the principal stress and strain directions and magnitudes. In the same manner, if we arrange three pairs of the SAW sensors as in a strain rosette, we can measure the fluid flow direction as well as the two-dimensional surface forces.

The size of a SAW device depends on its delay line length. The delay line length is usually betw-een 50-100 wavelengths of the SAW and the wavelength is determined by the center frequency of the sensor for each material. Thus by employing various center frequencies, we can achieve various size SAW sensors. Conventional SAW sensors operate at frequecnces from tens of MHz to one GHz. The advent of a good polymer-type piez oelectric material -PVDF- and the progress of fabrication and photolithographic technique allow a much wider frequency range, as in our SAW sensor. With this wide frequency range, the SAW sensors can be made in both large and small siz es. For the new SAW sensors, the large one of a low frequency will be used as a global turbulence sensor. It can measure the averaged surface forces over a long distance and show the global effect of turbulent flow. A small one fo high frequency will be used as a local SAW sensor which can measure th detailed effect of turbulent flow over a short distance. The specific size of the local and global SAW sensors will depend on the spatial and temporal resolution required.

Ⅶ. Conclusion

The concept of new SAW sensors for measur-ement of wall surface forces in laminar and tur-bulent flows was introduced and tested through experiment in both static and dynamic loading conditions. In the experiments, the velocity change of the SAW was measured in terms of either phase shifts or frequency shifts. As predicted, the measured velocity change shows linear relationship with applied pressure and shear stress. The velocity of the SAW is changing in opposite directions depending on whether the shear stress is compr-essive or tensile. Also, the sensor can document the temporal and spatial variation of the wall stresses. Therefore, the main concept of the SAW sensor was verified and the sensor can be used for the determination of wall pressure and wall friction on a structure embedded in laminar or turbulent flows. The range of applications of the SAW sensors in fluid dynamics is promising, as seen in the fundcamental studies [11] as well as the experimental tests carried out. Future work will include the refinement of the sensor as a routine tool for measuring normal stress and skin fricition associated with laminar or turbulent flows, and its application to practical situations.

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