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LOCAL/GLOBAL SAW SENSORS FOR TURBULENCE

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Abstract - A new surface acoustic wave (SAW) sensor is developed through theoretical and experimental investigation to detect the surface forces (wall pressure and wall friction) and the direction of the turbulent flow as a function of position and time on the structure. The sensor is composed of a pair of SAWs having an identical center frequency with surface waves experiencing shear stresses in opposite directions. The difference in the two SAW velocities is proportional to the shear stress associated with the turbulent flow. The difference between the mean velocity of a pair of the SAWs subject to a turbulent 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 can also be determined through an arrangement of three pairs of SAW sensors in a manner similar to a strain rosette. Depending on the spatial and temporal resolution required, we can simultaneously measure the fluctuating surface forces and the direction of a turbulent flow both locally and globally.

1 - INTRODUCTION

The determination of unsteady surface forces (wall pressure and wall friction) on a structure embedded in a turbulent flow is an important problem in fluid dynamics. A lot of theoretical and experimental work has been done to develop a good measurement technique for the space and time dependent surface forces in a fluid flow. This is because information about the surface forces can 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 turbulence by active methods. Hence there has been a strong need to develop a new sensor for turbulence which allows for both temporal and spatial resolution of surface forces.

A surface acoustic wave (SAW) is very sensitive to its environment. Here, the environment refers to any variable surrounding the SAW, such as temperature, humidity and external forces. When a SAW is exposed to these variables, a measurable velocity change proportional to the variable changes can be observed. If the environment is a turbulent fluid flow, the SAW velocity is affected by it. By employing this property of the SAW, we are developing new SAW sensors which can detect the surface forces and the direction of the turbulent flow as a function of position and time on a structure.

In this paper, we introduce the concept of new SAW sensors for turbulence obtained from the results of numerical simulation. Then we present the procedure and results of the experiments for normal pressure and shear stress measurement under static loading by the new SAW sensors. With the experimental results, we confirm the concept of new SAW turbulence sensors.

2 - THEORY

In Fig.1, there are three SAW sensors composed of a piezoelectric layer, a substrate and interdigital transducers (IDTs). All three sensors are identical including materials, IDTs and the center frequency. No fluctuating surface force is applied to SAW sensor A. It is immersed in a stationary fluid. Everything is stable and the SAW velocity $V_0$ of this sensor is used as a reference. Two other sensors B and C are subject to turbulent flow and the SAW experiences both normal pressure $P$ and shear stress $S$ given by the
turbulent flow. The magnitude of $P$ and $S$ for the two sensors is the same. But for sensor B, the right end of the piezoelectric layer is fixed and in the sensor C, the left end is fixed. For the two sensors, B and C, the application of the normal pressure $P$ has the same effect on both. But the shear stress $S$ for the two sensors will deform the layers of the sensors in opposite directions. The surface layer of sensor B will be compressed, while that of sensor C will expand. Hence, what the SAW experiences in sensor B is named compressive shear stress and, in sensor C, tensile shear stress. For the two sensors, everything is the same except whether the shear stress is compressive or tensile. Then in sensor B, the velocity of the SAW increases to $V_1 + \Delta V_1$, and in sensor C, the velocity decreases to $V_1 - \Delta V_1$. The common velocity $V_1$ of the two sensors is 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 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 set up the following equations.

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

\[
(V_1 + \Delta V_1) - (V_1 - \Delta V_1) = 2\Delta V_1 \propto S
\]

(1)

3 - DESIGNING SAW SENSORS

To check the theory of Sec.2, we designed a low frequency SAW sensor. It is composed of a PVDF film produced at Raytheon, a plexiglass substrate and silver electrodes. The SAW propagates in the stretched direction of the PVDF film. For measurement, the SAW sensor had to be immersed in liquid. For immersible SAW sensors, the propagating SAW would radiate energy into the liquid and hence suffer attenuation. Through numerical simulation, an optimal non-dimensional wave number $k_a$ ($k$: wave number, $a$: PVDF film thickness) was determined to get maximum SAW generation efficiency by the IDTs and minimum attenuation in the propagation. In the simulation, to determine the optimal geometry, all the material properties of PVDF had to be known, such as elastic, dielectric and piezoelectric constant tensors. But all of them are not yet available. Hence we had to make some approximations and made $e^{11} = e^{22} = e^{33}$ and $e_{34} = e_{35} = e_{33}$, which was a reasonable assumption.

A low frequency SAW sensor was designed based on the numerical results. A 0.53 mm thick PVDF film was attached to a plexiglass substrate with epoxy. Electrodes were drawn with silver paint after curing at the temperature of 60°C for 8 hours. The center frequency of the sensor was 702 KHz in air. The size of the sensor was $152\text{mm} \times 76\text{mm} \times 19\text{mm}$ (length x width x thickness). Because the thickness of the substrate was only over 11 wavelengths, the waves are not pure surface waves, but they are analogous surface waves.

4 - PRESSURE MEASUREMENT

For the measurement, the sensor was immersed in a tank filled with motor oil (density = 0.6) and the pressure applied to the delay line (surface of the piezoelectric layer) was controlled by changing the depth of the oil in the tank. As a liquid, motor oil was used instead of water to insulate the electrodes. But later, the electrodes were insulated with a Rho-C Rubber coating. The test equipment consisted of a LeCroy 9400A digital oscilloscope, a Panametrics pulse generator 5055PR and a Krohn-Hite 3202 filter. The oscilloscope could perform the FFT operations. All the measurements were made at room temperature. The change of the static pressure proportional to the depth of the oil caused a change of the SAW velocity. This velocity change was measured in terms of a phase shift. The results are shown in Fig.2. As seen in the figure, there is a linear relationship between the two variables, pressure and phase shift. The sensitivity was $1.5$° of phase shift per 1 cm change of oil depth. This value equaled $1.5$° phase shift for 60 Pa of pressure change. Because we could measure the phase shift up to $0.1$°, the sensor could sense the pressure change up to 4 Pa. If converted into a length scale, the pressure sensor could sense a change in oil depth of 0.67 mm (for water 0.4mm).

5 - SHEAR STRESS MEASUREMENT

The same SAW sensor was exposed to shear stress. Because the magnitude of the shear stress to be tested was so small, big testing machines could not be used. Instead, a small box made of Rho-C Rubber was put on the delay line and by means of a roller, weights was applied to the string, which converted into a shear stress on the sensor. In the experiment, to represent sensor B of Fig.1, we fixed the right end, and for sensor C, we fixed the left end of the PVDF layer with silver epoxy and a clamp. With the application of shear stress, the SAW velocity change was measured in terms of a phase shift. All measurements were made in the same manner as in the pressure measurement. Figure 3 shows the results of both the compressive and the tensile shear stress cases. The phases of the two sensors B and C started at the same value because the normal pressure was the same for both of them. As predicted, the phase shift of the SAW was proportional to the magnitude of the shear stress and the direction of the shift was opposite for the two types of shear stress. The magnitude of the velocity change was almost equal for the two cases. The phase
shift difference of the SAWs of the two sensors was proportional to the shear stress at the surface of the delay line. The addition of the compressive and tensile phase shift remained constant (0°) because the normal pressure was kept constant for both of the sensors. Therefore, these results confirmed Eq.1, the concept of new SAW sensors for turbulence. In the measurement, we obtained 1° phase shift per 10 Pa of each type of the shear stress. The SAW sensor was more sensitive to shear stress than normal pressure.

6 - CONCLUSION

Through numerical simulation, we have set up the concept of new SAW sensors which can detect the normal pressure and the shear stress given by the existence of a turbulent fluid flow. The sensors can detect both of surface forces and can also distinguish one from the other. In mechanics, with a strain rosette, we measure the principal stress and strain directions as well as the magnitudes. By arranging three pairs of the SAW sensors in the same manner as in a strain rosette, we can also measure the fluid flow direction and the two-dimensional surface forces. In addition, by arraying the SAW sensors in a row, we can measure the space dependent surface forces, and, measuring the change of the SAW velocity continuously, we can also get the time-dependent surface forces.

The size of a SAW device usually depends on its delay line length. The delay line length is usually between 50-100 wavelength 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 frequencies from tens of MHz to one GHz. With this wide frequency range, we can make SAW sensors of both large and small sizes. The large low frequency SAW sensor will be used as global turbulence sensors. It can measure the average surface forces over a long distance and show the global effect of a turbulent flow. A small sensor operating at a high frequency can be used as a local SAW sensor which can measure the detailed effect of a 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.

In conclusion, we have demonstrated the concept of new local/global turbulence SAW sensors. The turbulence SAW sensors can simultaneously measure the space and time dependent surface forces (the normal pressure and the shear stress) and the direction of a turbulent flow, both locally and globally.

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Fig. 1 - Concept of new SAW sensors for turbulence

Fig. 2 - Phase shift and pressure variation from the measurements with the SAW sensor

Fig. 3 - Phase shift and shear stress variation from the measurements with the SAW sensor