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論文内容要旨

1.Introduction

At a low Reynolds number, it is well known that the pressure fluctuation acting upon a solid body plays the central role in a generation of the aerodynamic sound. In a flow over a cavity, vortices which are formed in the separating shear layer generate the aerodynamic sound characterized by a single frequency peak and a large amplitude as a result of the feedback loop and resonance.

In the last decades, the reduction of the aerodynamic noise generation due to the flow behavior in and over a cavity have attracted great deal of attentions because of demands in practical applications. In most attempts, passive control devices have been used. However, the capability of passive techniques are limited within a specific geometry and flow conditions. Recently, active control of various flow fields have been attempted. An airjet, piezoelectric flaps, and an unsteady bleed forcing are typical devices tested for the cavity flow control. Most of the cavity flow and its sound control attempts have been based on either breaking up the vortex structures in the cavity or changing the dominant frequency of the oscillation.

On the other hand, the approach suggested in this research does not try to change the frequency from the natural dominant frequency of the flow over a cavity. The method tries to control only the timing of the perturbation at the upstream edge depending on the spanwise location so that the wavy patterns of the velocity fluctuation will have phase differences along the spanwise direction. If the velocity fluctuations which have 180 degrees phase difference can be created in the flow side by side in the spanwise direction, the pressure fluctuations hence the acoustic waves coming out will also be 180 degrees out of phase. Then it can be expected that the opposite-signed sound waves will eventually cancel each other faraway from the source, although the sound generation itself has not been reduced at the source. The advantage of this method is that it utilizes the natural dominant frequency of the structure in a cavity. As a result, very effective flow control and noise reduction control can be expected. A noise reduction attempt based on this concept were first tried out by Kikuchi *et al.* It was reported that the flow fields were successfully controlled and the resultant noise reduction effect could also be achieved. However, in the experiment using piezo-film (PVDF) as the controlling device, the control effect was found only under limited conditions.

The purpose of this research is to develop a technique for cavity flow control and the sound control which can be applied to a wide range of conditions. The conditions mentioned here include the geometry of the cavity, namely whether it is a shallow type or a deep type, and the character of a upstream boundary layer, whether it is laminar or turbulent. The concept is tested also in a large scale experiment, with practical appreciations, such as a high-speed train or an automobile, in view. For this purpose, two types of piezoceramic actuators and loudspeakers are tested for their effectiveness as the controlling devices.

2. Active Control of the Flow over a Shallow Cavity with Laminar Separation

In this chapter, the control for the simple flow environment that was a combination of a shallow type cavity and a laminar separation is attempted. In this type of a cavity, where the wavelength of the sound is much longer than a characteristic length of a cavity, only the shear layer instability and its feedback loop play major roles in the sound generation.

The aim of this chapter is to develop a method to control the flow and reduce the noise under a wide range of conditions and to overcome the difficulties Kikuchi *et al.* encountered. In the investigation, two types of piezoceramic actuators are tested. One is the "Unimorph type" actuator and the other is the "Bimorph type" actuator. They move their trailing edge parallel or vertical to the freestream. The effectiveness of each of the two actuators to control the flow and the sound generation is examined. Judging from the basic properties of the piezoceramic devices, piezoceramic was expected to be able to introduce stronger fluctuation into the flow, compared to the PVDF actuator. The upstream edge of the cavity was selected as the location to place the actuators because of its high receptivity. The influence of the wavelength of the velocity fluctuation pattern along the spanwise direction to the effectiveness of the control is also investigated.

Experimental results showed that wavy patterns which have 180 degree phase difference along the spanwise direction could be created using either the unimorph type or the bimorph type actuators. It was tested at the same condition for which the PVDF actuator could not achieve the control. Only the phase of the velocity fluctuation could be controlled without influencing the other flow properties. However, the flow field controlled by the bimorph type actuators showed indication of the streamwise vortices.

As a result of the flow control, reduction of the aerodynamic noise was achieved when the unimorph type actuator was used. On the other hand, the bimorph type could not reduce the peak sound level under most of the conditions, even when the control of the flow field appeared to be successful. These failure in the control may be partially due to the self-generation of the noise from the actuators themselves as well as the imperfectness in the control of the flow field.

By using eight pieces of the unimorph type actuator, it was shown that this system could create wavy patterns of velocity fluctuation having various wavelengths in the spanwise direction. The results also showed that the most effective wavelength depends on the magnitude of the velocity fluctuation in the boundary layer. The analysis using spanwise averaged value of the ensemble-averaged velocity fluctuations disclosed the relation between the three-dimensionality of the velocity fluctuation pattern and the level of the cavity noise reduction.

From the experimental results, it was shown that the system was capable of creating wavy pattern of velocity fluctuation in the shallow type cavity flow field with laminar separation. It was also shown that the unimorph type actuator is superior to the bimorph type actuator not only for the flow control but especially as a device for the aerodynamic noise reduction.

3. Control of the Flow over Cavity and its Sound Generation when the Upstream Boundary Layer is Turbulent

In this chapter, more advanced controlling technique is applied to a deep type cavity. In this type of a cavity, it is known that a complex mechanism that consists of a shear layer instability(feedback type) and an acoustic resonance inside a resonator affects the sound generation. The experiment to control the flow was tested under the condition that the upstream boundary layer was turbulent and the freestream velocity was comparatively low, because in practical situations, most of the boundary layers approaching cavities are turbulent.

In order to excite wavy patterns, two types of the piezoceramic actuators are used. Unlike the experiment described in chapter 2, the bimorph type actuator is attached onto the vertical wall of the upstream side of the cavity so that its edge will move in the streamwise direction, while the unimorph type is still glued on the flatplate surface. The effectiveness of two types of actuators placed at two different locations are compared.

As a result of the investigation employing the power spectrum and the wavelet analyses, it was revealed that the flow structure and the cavity tone has a "cause-and-result" relation. This result gave the basis to the rationality of the current study's approach, which is to control the flow field structure in order to control the sound field.

When the unimorph type actuator was used, the flow field could not be controlled as was intended. Only a small breakdown of the vortex structure could be seen which resulted in a small reduction of the cavity sound level. On the other hand, adding partition plates combined with the unimorph actuator control proved to be very effective. However, the wavelength was not always as was intended due to the introduction of unfavorable fluctuations.

The configuration, in which the bimorph type actuator was set vertically at the upstream edge of the cavity, completely controlled the flow field and greatly reduced the cavity sound. The reason for its effectiveness for the deep type cavity flow control can be estimated that the actuator can influence both the outside shear layer instability and the pressure field inside the cavity at the same time. It was also revealed that the shorter spanwise wavelength is preferable not only for the flow control but also for the noise reduction when the upstream boundary layer is turbulent. The analysis using spanwise averaged value of the velocity fluctuations clearly and quantitatively disclosed the difference between the effectiveness of the unimorph type and the bimorph type actuators, and also the effectiveness of the partition plates.

It was shown that even for a complicated flow environment, the concept and the system used in the current research were capable of creating wavy pattern of velocity fluctuation. It should be especially noted that, in this research, the noise reduction was successful when the freestream velocity was lower than M $= 0.2(U_\infty = 30.0\text{m/s})$, which had not been reported in other researches in the past.

4. Large Reynolds Number Experiment

The large scale experiment is conducted at the Large-Scale Low-Noise Wind Tunnel of the Railway Technical Research Institute, where the high Reynolds number based on the boundary layer thickness at separation point reaches Re_δ=5.2×10^5. This Reynolds number is more than an order of magnitude larger than the Reynolds number Re_δ=1.6×10^4 in the experiment described in chapter 3. The geometry of the cavity used is classified into a "deep cavity" type. Two types of the piezoceramic actuators that were glued onto the flatplate surface of the upstream edge of the cavity, and an array of loudspeakers equipped at the bottom of the cavity were tested as the controlling devices.

The objective of the research in this chapter is to achieve the flow control and the resultant noise reduction against a high Reynolds number turbulent separating flow. The experiment should show whether or not the control method in this research can be useful when applied to an actual high-speed train or an automobile. In addition, the relation between the characteristics of the fully turbulent separating flow over a cavity and the generated sound is examined and discussed.

The dominant frequency of the sound varied not with the freestream velocity but rather depending on the cavity depth. When the freestream velocity was 60.0m/s, the frequency of the shear layer oscillation agreed well with the resonance mode for cavity depth of 650mm. On the contrary, when the freestream velocity was 70.0m/s, the interaction did not take place compared to the 60.0m/s case. As a result of the investigation of the relation between the wall surface pressure and the velocity fluctuation over the cavity, it was revealed that the velocity fluctuation hardly show any periodic patterns while an outstanding peak can be found in the pressure spectrum.

A clean noise reduction effect could not be found by any of the experiments using three types of controlling devices. The bimorph type actuator gave the best results when the partition plate was not installed. The results using the unimorph type with the partition was reasonable. However, the control effect was insufficient. The loudspeaker was effective only in the Single-phase control mode. The partition plates showed only a limited advantage in this experiment.

The power spectra measured by the hot-wire anemometer revealed that the bimorph type actuator could introduce a velocity fluctuation with spanwise phase differences. However, the structural pattern could not be identified in the results of the wavelet analyses even when the actuator was in operation. There maybe two reasons, one is that the pattern of the dominant mode which contains a large energy have been buried in other components of the turbulent random field, the other is the fact that the piezoceramic actuators were not relatively large enough to influence the flow. However, the fact that the flow partially responded to the control implies that the attempt was not a completely a failure either. The experimental results are not sufficient to draw a conclusion on whether the flow controlling concept tested in this research is capable of reducing the cavity noise or not at high Reynolds number conditions.

5. Conclusion

As a result of series of experiments, it was revealed that when the cavity flow field has two-dimensional vortex structure, the piezoceramic actuator can create the spanwise phase difference of velocity fluctuation even for the turbulent separating flow regardless of the cavity type, a shallow one or a deep one. And in those conditions, the aerodynamic sound from cavity-flow system could be successfully controlled. The bimorph type actuator appears to be superior to others because it showed the advantage in introducing velocity fluctuation and creating structures. However, when it is used incorrectly, the self-generated noise from the actuator can become larger than the original noise. It also has a danger to generate streamwise vortices. On the other hand, if the main structure is embedded in the turbulent random structures, even if a two-dimensional structure exists, it is found to be very difficult to control both the flow and the sound. This case will remain as a subject for the future study.

論文審査結果の要旨

本論文は、キャビティ騒音をスパン方向に位相差を有する速度変動波を導入することで抑制することを目的とした実験的研究である。上記の目的に対し、まず、浅いキャビティ上の層流はく離流の制御を行い、次により複雑かつ困難となる深いキャビティ上の乱流はく離流の制御を可能にする手法を確立している。さらにそれらを実用スケールの流れ場の制御に応用し、キャビティ音の抑制に有効な制御技術を開発した成果を全編5章にまとめている。

第1章は緒論であり、本研究の背景、基礎理論および目的を述べている。

第2章では、浅いキャビティ上の層流はく離流および発生音の制御を、振動形態の異なる2種類のピエゾセラミック製のアクチュエータを応用したシステムにより行い、制御装置としての有効性を比較している。いずれも従来の制御で指摘されていた導入される変動が弱過ぎる問題を克服し、広範囲の条件下への適用を可能とした実用性の極めて高いシステムであることを示している。また、アクチュエータの形態の違いが制御結果に与える影響を明らかにし、主流速度、境界層内乱れ強さなどの流れの条件と、ピーク音抑制に最適な速度変動波のスパン方向波長との関係を見出している。これは重要な成果である。

第3章では、第2章で構築されたシステムを、共鳴管付きの深いキャビティ上の乱流はく離流および発生音の制御に適用している。アクチュエータと仕切り板を組み合わせる制御を行うことで、強い速度変動波の導入と騒音レベルの低減に成功している。また、流れ場をより効率的に制御し騒音レベルを大幅に低減する方法として、制御装置をキャビティ上流側ではなく内部に設置し主流方向と平行に振動させる手法を提案し、その極めて高い有効性を実証している。これは工学的に重要な成果である。

第4章では、対象を実用スケールに拡張し、大型低騒音風洞における実験を行っている。3種類の制御装置を用いた実験の結果、実用スケールにおいても本研究で構築したシステムにより速度変動波を導入することが可能であることを実証している。さらに、効果的な制御を行う前提として自然状態の流れ場に2次元的な渦構造が存在していることが重要である点を明らかにし、さらに制御装置と上流側境界層の代表スケールの関係についても検討している。これらは実用化の観点から極めて有用な知見である。

第5章は結論である。

以上要するに本論文は、キャビティ上のはく離流を制御する各種の方法を提案し、速度変動波と発生音の関係を解明し、キャビティ音抑制の具体的方法を検討した内容をまとめたものであり、流体工学ならびに空力音抑制技術の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。