氏名	易　東来
生年月日	
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学位授与の題目	Fluid-dynamic Forces Acting on and Flow Patterns Around an Oscillating Rectangular Cylinder （振動角柱周りの流れと流体力特性に関する研究）
論文審査委員	（主査）岡島　厚 （副査）石田　啓，上野久儀 森　茂，木村繁男

学位論文要旨

Flow around bluff bodies and the associated flow-induced oscillation phenomena have numerous practical engineering applications in addition to their importance in a fundamental physical sense. With lighter and thinner materials being used in modern structures, the failure of structures caused by flow-induced vibrations is experienced in a wide range of industries. The low-speed instability and its associated fluid-dynamic and fluid-elastic characteristics are particularly important in the sense that it occurs at low speed condition under which the damages are not expected to but actually do occur due to fatigue failure. Therefore, the studies on low-speed instability and its fluid-dynamic and fluid-elastic characteristics of an oscillating rectangular cylinder, which is the basic structural component of a lot of engineering structures, become more and more important.

While **Chapter 1** is an introduction to the present studies, **Chapter 2** gives an intensive review on previous studies in the area of flow-induced vibrations of circular and rectangular cylinders under both free- and forced-vibrations in transverse, streamwise and rotational directions.

Fluid-dynamic forces acting on, fluid-elastic characteristics of and flow patterns around a rectangular cylinder with cross-sectional side ratios of 1, 2 and 3 under forced transverse and in-line oscillation are studied intensively in this paper in both experimental and numerical methods.

Chapter 3 addresses the experimental results of force measurements and visualization on the flow around a rectangular cylinder with cross-sectional side ratios of 1, 2 and 3 under forced transverse oscillations. The cylinders were forced to oscillate transversely in a uniform

flow at different frequencies and at amplitudes of 3.5%,14% and 28% of the shorter side H. Measurements were made on the lifts, drags and phase angles of lift forces with respect to body displacements of the rectangular cylinder. Force measurements show that there exist peaks in C_D and C_L curves respectively as St_c increases. The C_D values of oscillating square cylinder after the peak are almost constant and much smaller than the values before the peak, while those of rectangular cylinders with B/H=2 and 3 after the peak remain almost the same values as before the peak. The C_L values after the peak reaches a minimum value and then increases gradually due to the inertia forces of flow. Measured phase angles show that, for square cylinder, there exists a low-speed instability in low speed range centered at about St_c=0.26 other than the galloping and vortex excitation instabilities in high speed ranges. As St_c further increases, the low-speed instability gradually disappears with phase angles approaching zero. For B/H=2 and 3 cylinders, there exist also such low-speed instabilities in low speed ranges centered at about St_c=0.2 and 0.18 respectively. It gets further assured that the low-speed instability occurs at a smaller St_c with increasing the side ratio of rectangular cylinders. The region of low-speed instability is narrow when the Reynolds number is small, and it is much wider and phase angles much larger for a smaller amplitude. It agrees well with free-oscillation tests, in which the low-speed instability range is wider with smaller free oscillation amplitude. The low-speed instability is aerodynamically featured by sharp decreases of C_D and C_L values after passing over their peaks.

Flow visualization shows that the wake flow of an oscillating rectangular cylinder goes through three stages with increasing forced oscillatory frequency, i.e. full-separation, alternate-reattachment and full-reattachment. At the full-separation stage, the shear layers roll up downstream in a way far from the trailing edges of afterbody. There is no reattachment of shear layers to the afterbody. The shear layers from upper and lower leading edges interact directly with each other and form a vortex street in the wake. Here we emphasize the strong interaction of upper and lower shear layers and refer the vortex street formed after such interaction as strongly-interrelated type. As St_c increases, the shed shear layers get curved and finally it comes the alternate-reattachment stage at which the shear layers will reattach with one trailing edge but separate from the other trailing edge in one typical oscillatory circle. In this stage, the shear layers are deflected to shed further downstream by tailing edges of afterbody, but they still interact strongly with each other and form strongly-interrelated type of vortex street in the near wake. With further increase of St_c, the alternate-reattaching point gets more and more upstream and it comes the third stage, i.e. full-reattachment stage where shear layers over both upper and lower sides get reattached with side faces of the oscillating cylinder. The two shear layers from upper and lower sides do not interact or only have very weak interaction with each other in the near-wake. They shed their own vortices independently, with each vortex street being parallel and almost on the extension line of each side surface. We term this vortex street as weakly-interrelated type.

The flow feature of vortex excitation is that the shear layers of strongly-interrelated vortex shedding interacts with the afterbody of cylinder, which performs most strongly at the initial stage of alternate-reattachment flow regime, whereas the flow feature of low-speed instability is the weakly-interrelated vortex street at the stage of full-reattachment. It should be emphasized that for B/H=3 cylinder, there is no vortex excitation and galloping instabilities. Some researchers regarded the instability range centered at about St_c=0.18 as vortex excitation instability. But it is actually low-speed instability, because visualization shows that there are no full-separation and alternate-reattachment flow patterns for B/H=3 cylinders at the present Reynolds numbers.

Chapter 4 addresses the experimental results of force measurements and visualization on the flow around a rectangular cylinder of B/H=1, 2 and 3 under forced in-line oscillations. Here also, force measurements were made on the lifts, drags and phase angles of lift forces with respect to body displacements of the rectangular cylinder. It is shown that C_D doesn't have great increases which are experienced by a circular cylinder under in-line oscillation; instead, the C_D values only show some small increases corresponding to the *AVL* region. C_L also only increases a little at very high forced frequencies, in contrast to the great increases at transverse oscillations due to large inertia forces.

Also addressed are the frequencies of vortex shedding. It is found that, as St_c increases, the vortices can shed in three different frequencies, based on which the wake flow features can be divided into three kinds. One is the Natural Vortex Shedding (*NVS*) region, where dominant shedding frequency is the natural frequency. The other is the Symmetric Vortex shedding Lock-in (*SVL*) region, in which the vortex shedding is synchronized with or locked into the forced oscillation in such a way that the vortices shed almost symmetrically in near-wake and in the same frequency with the forced one. The third is the Alternate Vortex shedding Lock-in (*AVL*) region, where the vortex shedding is locked into half of the forced frequency, i.e., each side of the cylinder sheds one vortex every two vibration cycles and forms alternate vortex street in the near-wake. The *AVL* region of square cylinder is centered at about double the natural Strouhal number St_n. The vortices can also shed sometimes in different combinations of natural shedding frequency f_n and forced oscillatory frequency f_c, as shown by the second or the third peaks of the spectrum analyses. The vortex shedding can be easily locked into forced oscillations both in *AVL* and *SVL* regions.

Visualization shows that for all cases, a pair of symmetrical vortices forms along the side surfaces and rolls up to shed downstream symmetrically. The symmetric wake finally develops into antisymmetric vortex street. With the increase of forced Strouhal number, the symmetric part of wake keeps longer. Furthermore, the width of wake becomes apparently narrow as the St_c of oscillation increases. As well known, the flow passing a stationary cylinder, either circular or rectangular cylinder, has an inherent or natural tendency to form an asymmetric mode of vortex shedding. On the other hand, when a cylinder is forced to oscillate in-line with the incident flow, the in-line motion imposes a symmetric perturbation to the flow. The interaction of these two effects is responsible for the dynamic characteristics and flow structures. Whether or not the symmetric modes of vortex shedding will prevail in the wake depends on whether or not the effect of forced perturbation on flow can overwhelm the inherent tendency of flow. Therefore, at high ratios of St_c/St_n (or f_c/f_n), the wake tends to become more symmetric and more narrow. As St_c/St_n increases, the change of flow structures from antisymmetric to symmetric is in such a way that the symmetric part of the wake increases gradually although the far wake is still antisymmetric. More important is that the wake flow is very unsteady, with the two vortex shedding models always appearing intermittently. Even at high forced frequencies, although the vortex shedding keeps symmetric in the near wake, the intermittent appearance of symmetric and antisymmetric vortex street is observed in the middle or far wake.

Chapter 5 presents numerical simulations of the flow around an oscillating rectangular cylinder of side ratios of B/H=1, 2, and 3 under both transverse and in-line oscillations. The Direct Simulation method is used. For transverse oscillation, both two- and three-dimensional simulations were conducted. For in-line oscillations, only two-dimensional simulations were conducted. Both two and three dimensional simulations successfully captured the main aerodynamic and aeroelastic characteristics of the flow around an oscillating rectangular cylinder, although relatively larger discrepancies are found for two dimensional simulations. The numerically simulated lift and drag coefficients, frequencies of vortex shedding, flow patterns, and angle phase differences between the lifts/drags and cylinder displacements agree with those of experiments. It is confirmed that three dimensionality accounts a large component for the discrepancies between the two-dimensional simulations and experiments of transverse oscillations, as the three-dimensional simulations do narrow the discrepancies between the computations and experiments. Other components of the discrepancies may result from the turbulences of flow in experiments. To remove these parts of discrepancies, turbulent simulation model is needed.

Chapter 6 deals with the effects of wall confinement on the aerodynamic characteristics of an oscillating rectangular cylinder. The experiments were conducted in the same open water tunnel as in Chapter 3 and Chapter 4 at different blockage ratios up to 37.5%, with rectangular cylinders of side ratios of B/H=0.5, 1, 2, 3 and 4 being forced to oscillate at different frequencies and amplitudes. It is found that the drag forces acting on oscillating B/H=1 and 2 cylinders decrease to certain values at first and then increase with increasing blockage ratios, while those acting on B/H=3 and 4 cylinders do not behavior so. The lift forces don't show much changes along the blockage ratios especially at middle and low forced oscillatory frequencies, although the lift forces at high forced frequencies show some changes especially for long-afterbody cylinder at large oscillating amplitudes. The effects of wall confinement on phase angles behavior in such a way that, on one hand, a higher blockage ratio results in a right-oriented shift of phase curve (velocity effect), and on the other hand, it also results in a left-oriented shift of the phase curves due to the easy reattachment (flow-pattern effect). The final effects are combination of velocity effect and flow-pattern effect. For the effects of wall confinement on vortex shedding Strouhal number, as long as it is locked into the forced frequencies, it keeps the same as the forced frequencies and never changes with blockage ratios. When it is not locked into the forced oscillatory frequencies, however, it will increase with blockage ratios and can be corrected with the described method.

学位論文の審査結果の要旨

平成８年１月26日，第１回学位論文審査委員会を開き，２月７日口頭発表を行い，同日第２回審査委員会を開催した。協議の結果，以下の通り判定した。申請者は中国・清華大学水利工程系卒業，水利水電科学研究院修了後，文部省国費留学生として本研究科システム科学専攻に入学した。申請論文は，構造物の空力弾性的不安定振動（フラッタ）発生機構解明のため，振動角柱周りの流れと流体力特性に関して研究している。まず流れに直角方向に角柱を並進振動させ，抗力，揚力，揚力の位相差を測定し，同時に流れパターンを水素気泡法により可視化し，渦励振，ギャロッピング，低風速励振などの不安定振動発生の際の揚力の位相差の急激な変化と流れパターン変化の密接な対応を見い出した。次に流れ方向振動の場合，自然発生後流渦，対称渦列，交互渦列の形成領域，ロックイン，非ロックイン領域に初めて分類した。さらに，差分法による２次元および３次元数値シミュレーション（直接法）を行い，３次元計算結果が実験結果に良く合うことを示し，３次元計算の重要性を強調した。最後に，流体力に及ぼす壁効果の研究から，アフターボディーのある場合，壁効果に依って剥離せん断層の再付着など流れパターン変化を伴うため，従来の円柱等に適用された修正法は不適切であることを見い出した。以上，要するに申請論文は，構造物のフラッタ発生機構の解明のため，振動角柱周りの流れと流体力特性に関して系統的な実験と数値シミュレーションを行い，種々な貴重な新しい現象を見出し，解釈を与えた。本研究成果は今後の構造物のフラッタの研究に資するところ大であり，博士（工学）論文として充分に値するものと認定する。