AN EXPERIMENTAL STUDY OF FLUCTUATING LIFT ON A
SQUARE-SECTION CYLINDER OSCILLATING TRANSVERSELY
IN A UNIFORM STREAM *

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ABSTRACT: Experiments on a square-section cylinder fixed and forced to oscillate transversely in a uniform stream were conducted in a water tank. The Reynolds number of the experiments is in the range of $3 \times 10^3$ to $10^4$, the amplitude to side length ratio $A/D$ is up to 0.7 and the range of reduced velocity is $4.5 < V_r < 12$. This study aims at investigating the lock-in phenomenon, the fluctuating lift and the phase shift between fluctuating lift and displacement of the oscillating cylinder. The problems on the aeroelastic instability relating to present experimental results have been discussed. The flow visualization clearly shows that there are drastic changes of vortex-shedding from cylinder at the resonance point and the upper end of the lock-in range. The results of the flow visualization give better understanding of the physical mechanism of the phase shift.

KEY WORDS: oscillating cylinder, fluctuating force, vortex-shedding, near-wake, lock-in

I. INTRODUCTION

Flow-induced vibration of a bluff body in a cross-flow is a very important and interesting problem in fluid dynamics as well as in practical applications. A bluff body placed in a flow may experience a transverse fluctuating lift force caused by the asymmetric formation of vortices, which can cause a structure to oscillate transversally. When a cylinder is forced to oscillate at a frequency $f_c$ which is in the vicinity of natural vortex-shedding frequency $f_{vs}$, a synchronization phenomenon occurs. Over the lock-in range, a maximum fluctuating lift force is excited. During the past few decades, numerous researchers have been working on this subject. Some of the results were discussed by Sarpkaya \cite{11} in a review. Many of the investigations, however, are concerned with the circular cylinders, and a comparatively few experiments have been made for a square-section cylinder oscillating in a crossflow. In recent years, Otsuki et al. \cite{21}, Nakamura & Mizota \cite{31}, Bearman & Obasaju \cite{41}, Obasaju \cite{51}, Bearman & Luo \cite{61}, and some others have conducted experimental studies on square-section cylinders forced to oscillate transversely with two faces normal to the flow. The lift, drag force and pressure fluctuation were measured in wind tunnels. The sudden change in phase angles between the transverse force and the cylinder displacement has been revealed in the lock-in region, and in these papers, the limitation of the applicability of quasi-steady theory suggested by Parkison \cite{71} has been discussed on the basis of experimental results. But some issues remain unresolved, such as the physical mechanism of the above phenomena. Hence the main aim of the present study is to measure the Strouhal number of vortex-shedding with hot-wire anemometer and the fluctuating lift acting on a square-section cylinder in the uniform flow either forced to oscillate transversely or fixed. We use electrolytic precipitation method to visualize the drastic change of the flow field around the cylinder in the lock-in range in order to explain the physical mechanism of phase shift near the resonance point. We also discuss the aeroelastic instability of the oscillating square-section cylinder. Experimental conditions are as follows: Reynolds numbers range from 300 to $10^4$, amplitudes from $0.13D$ to $0.7D$ ($D$ is the side length), and the reduced velocity ranges from 4.5 to 12.

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II. EXPERIMENTAL SETUP AND METHOD

The experiments were conducted in a towing water tank at the Institute of Mechanics, Academia Sinica. This tank is 0.5m deep, 0.4m wide and 6m long. The carriage speed is controlled by an electric-speed motor.

The square-section cylinder is 360 mm long and has a side length of 33 mm. To minimize three dimensional effects in the flow, the cylinder is divided into three sections. The upper and lower sections, which are used as dummy cylinders, are connected to each other with a rod. The central section is 120 mm long and suspended vertically from a small load cell mounted inside the upper dummy cylinder. One Scotch-yoke mechanism fixed on the carriage forces the cylinder to oscillate sinusoidally in the direction transverse to that of the flow. This mechanism can be modified to increase its maximum amplitude to 80 mm. The displacement signals of the cylinder are provided by a resistance transducer. The signals of force and displacement of the cylinder are recorded simultaneously using an A/D converter and analyzed on a Super /XT computer. The signals of inertia forces are removed from those of the total forces. The ratios of the amplitude of oscillation to side length \( A/D \) are 0.13, 0.25, and 0.7. The Reynolds number is in the range of \( 3 \times 10^3 \) to \( 10^4 \) for force measurement and is 300 for the flow visualization. The range of reduced velocity is \( 4.5 < V_r < 12 \).

The vortex-shedding frequency \( f_s \) is measured by a hot-wire anemometer mounted at about 5D downstream of the cylinder. The flow field around the cylinder is visualized using the electrolytic precipitation method. The solder is coated at the middle of the cylinder surface as an anode so as to give detailed information regarding the flow separation and reattachment phenomena near a square-section cylinder. A slide projector is used to illuminate the flow field from the side wall of the tank and the photograph is taken from the top of the tank.

To investigate the variations in the flow field of the near wake and the phase shift of the vortex-shedding, all the photos are taken at the moment corresponding to the maximum negative displacement of the cylinder motion (the upward direction being defined as positive).

III. EXPERIMENTAL RESULTS

3.1 Results for a Stationary Cylinder

Vortex-shedding frequency from the stationary square-section cylinder in the uniform flow, is measured by a hot-wire anemometer for Reynolds numbers in the range of \( 150 < Re < 5000 \), and is represented by Strouhal number \( S_{st} = f_s \cdot D/u \). The experimental value of Strouhal number is about \( S_{st} = 0.148 \) in the lower Reynolds number range \( 150 < Re < 300 \) and \( S_{st} = 0.135 \) when \( 300 < Re < 5000 \).

Measurement of fluctuating lift coefficient made on the stationary square-section cylinder is plotted against Reynolds number in Fig. 1, where \( C_L = F_{Lrms}/(\frac{1}{2} \cdot \rho \cdot u^2 \cdot D \cdot L) \) and \( F_{Lrms} \) is root-mean-square value of fluctuating lift. It can be seen from Fig. 1 that the coefficient \( C_L \) increases linearly with increasing Reynolds number, which shows a similar trend to the result of [6] in which \( 10^4 < Re < 8 \cdot 10^4 \).

3.2 Experimental Determination of lock-in Region

As above mentioned, the synchronization phenomenon should take place when the frequency forcing a cylinder to oscillate is nearly at the natural vortex-shedding frequency that could be measured behind a stationary cylinder for the identical flow condition. In this case, the vortex-