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THE EFFECTS OF THREE-DIMENSIONAL IMPOSED DISTURBANCES ON BLUFF BODY NEAR WAKE FLOWS

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Effects of Three-Dimensional Imposed 3-D Disturbances on Bluff-Body Near Wake Flows

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PROJECT ABSTRACT

Research Goals:

This experimental research effort focuses on the underlying three-dimensional flow structure in the near wake of a bluff body when subjected to imposed geometrical disturbances. To understand the effects of three dimensionality that are characterized by vortex splitting and looping and how they are related to other wake parameters such as base pressure shedding frequency, wake width and wake formation length.

The long term goals:

1. To gain an improved understanding of the effects of imposed three-dimensional disturbances on the flow structure in the near wake of a nominally two dimensional bluff body.

2. To determine the effects of certain approach flow nonuniformities on the development of the near wake of infinite and finite aspect ratio circular cylinders with and without imposed three-dimensional disturbances (splitter plates) at high Reynolds numbers.

Objectives:

1. To obtain a fundamental understanding of the three-dimensional features that arise in the near wake flow region behind nominally two-dimensional bluff bodies subjected to imposed mild three-dimensional disturbances for purpose of flow control. Controlled three-dimensional disturbances will be introduced into the near wake flow of a circular cylinder by a spanwise periodic trailing edge splitter plate and into the near wake of a blunt based section by a sinusoidal-trailing edge.

2. To study the instantaneous occurrence of vortex looping and dislocations which occur in the near wake as result of the imposed three-dimensionality and visualize the various shedding modes.

3. To study the three-dimensional features that arise in the near wake region behind a nominally two-dimensional bluff body due to certain approach flow nonuniformities such as a linearly varying shear flow.

Approach:

The body shape studied was a 2 in (5.08 cm) circular cylinder with a cylinder length to diameter ratio of 12 with a groove along the wake centerline to accommodate splitter plates. Experiments were performed on two-dimensional splitter plates of varying plate length as well as spanwise periodic trailing edge splitter plates of varying amplitude and wavelength. The plates used in this experiment had the dimensions ℓ/D=0.625, 1.0, and 2.0; a/D=0.5, 0.875, 1.875; and λ/D=3.0, 2.76, 2.36, 2.07. The three dimensional structure of the near wake was investigated using wind tunnel and water tunnel experiments. Wind and water tunnel facilities at U. of Notre Dame and at Imperial College in cooperation with Professor Peter W. Bearman were utilized. The Reynolds number range in the wind tunnels was 20,000 to 50,000 and 2700 to 7550 for the flow visualization in the water tunnels. Hot-wire anemometry was used for velocity and velocity fluctuation measurements. Instantaneous pressure measurements and flow visualization via smoke wire in the wind tunnel and lead precipitation in the water tunnel were integrated with velocity measurements to reveal the three-dimensional character of the near wake.

Tasks Completed:

- Velocity and pressure measurements have been completed for a circular cylinder with a two-dimensional splitter plate with varying plate to diameter ratios as well as a circular cylinder with a spanwise periodic trailing edge splitter plate with varying plate to diameter ratios, and varying wave length and amplitude. These experiments were carried out in a Reynolds number range 10,000 to 50,000. Smoke wire and smoke rake flow visualization were used to observe the three-dimensional feature in the flow.

- Flow visualization using electrolytic precipitation was used to observe the flow over these same model in a water channels at Imperial College and the University of Notre Dame at a Reynolds number of 5,000-8000.

- Two shear screens which produce a linear shear profile provided the capability of operating in two different aspect ratio wind tunnels. The shear screens had a shear gradient, du/dz = 8.66 and 6.40 1/sec; a steepness parameter $\beta = du/dz(D/U_{ref}) = 0.04$ and 0.03: and shear parameter $\lambda=\beta H/D = 0.32$ and 0.36 respectively. Linear incoming shear flow produced spanwise cell structure to the flow and other modifications to the near wake.

- A tapered cylinder in a uniform and in a linearly varying shear flow have been studied and produced yet another three-dimensional structure in the near wake. However, the most notable feature of near wake flows behind bluff bodies, namely vortex dislocations was maintained.

Scientific Results:

The present work indicates that wakes behind a circular cylinder with a periodic trailing edge splitter plate differs from the wake behind circular cylinder and the wake behind circular cylinder with a two-dimensional splitter plate. The presence of a spanwise periodic splitter plate affects the mean and fluctuating base pressure along the span which in turn modifies the vortex shedding modes. With the introduction of a two-dimensional splitter plate, the shedding frequency decreases to a minimum as the plate length was increased to a plate to diameter ratio of one, and then increased with larger plate lengths. Hence, when the formation length increased with the introduction of splitter plates, the Strouhal number decreases. Due to the longer formation length region, the shear layers elongate resulting in more vorticity diffusion in the shear layers that causes the shedding frequency to decrease.

For the periodic splitter plates the values of the shedding frequency at the peak and valley fell between values for the two equivalent two-dimensional splitter plates respectively. However, a spanwise variation in the shedding frequency is observed i.e., as a probe is traversed from valley to peak, a second frequency appears in the spectra and is as dominant as the shedding frequency when the peak is approached whereas it is virtually nonexistent at the valley. This presence of a second shedding frequency leads to vortex dislocation and is manifested by the spanwise periodicity introduced by the periodic splitter plate.

Instantaneous base pressure measurements on the cylinder with spanwise periodic trailing edge splitter plate disturbances indicate a direct coupling to the shedding frequency. A strong correlation existed between the stagnation-line and base pressure signals. A low frequency component in the base pressure power spectra was found and was directly related to an irregular shedding mode observed in the wake. This observed low frequency corresponds to the dislocation frequency observed in the spectra obtained from hot-wire traverses.

Flow visualization experiments using the electrolytic precipitation method have clearly indicated several modes of shedding and strong three dimensionality that include vortex splitting and vortex dislocations. It was found that for certain splitter plate length to diameter ratios, for those below the minimum drag condition, the shedding pattern became very regular and two-dimensional in spite of the geometrically imposed three dimensionality in the near wake. Frame by frame analysis of the flow visualization video shows an instantaneous mode selection of twice the frequency of the input spanwise periodic splitter plate. Flow visualization results indicate that there exists a feedback mechanism of the spanwise periodic trailing edge structure to the vorticity shed at the separation line. The effects of the input wavelength and amplitude have yet to be determined and how they relate to the fundamental features of vortex dislocations.

The tapered cylinder ($dD/dz = 0.031$) in the uniform flow configuration produced three constant frequency spanwise cells. The cell structure was similar to the cells produced by the straight cylinder in shear flow however the shear layer in the taper-uniform flow configuration indicated a much more 2-dimensional behavior. The local non-dimensional formation length increased with decreasing cylinder diameter across the span. This was due to the strong spanwise coherence of the shear layer and the uniform external flow that kept the Kármán vortices relatively parallel to the cylinder axis.

An overall increase in the number of dislocations, vortex pairing events, and the irregular formation of transition vortices show that the shear flow significantly increases the 3-dimensionality of the shear layer compared to the uniform flow configurations. In all of the uniform flow configurations, including the tapered cylinder, the shear layer was relatively 2-dimensional.

Finally, the combined effect of shear flow and cylinder taper was investigated. The cylinder was oriented in the flow so that, assuming a constant Strouhal number based on local conditions, the shedding frequency would be constant across the span. This assumption was found to be valid and a constant shedding frequency was produced. A cylinder with slightly larger taper ratio, dD/dz = 0.042, was also investigated. This configuration produced a spanwise constant frequency cell structure. It was concluded from these results that if a constant local Strouhal number is maintained along the span of a bluff body with mild 3-dimensionality, a constant shedding frequency can be produced.

The applicability of a two-dimensional strip theory approach for bluff bodies with mild 3-dimensionality was also considered and appears to be a valid and useful approach to predicting the shedding characteristics of the bluff body provided information regarding the spanwise coherence length scale (cell size) is available. However, prediction of the cell size is difficult and appears to be dependent on the level of 3-dimensionality in the flow, i.e. shear gradient, cylinder taper, turbulence level, etc. The usefulness of the strip theory depends on the accuracy required in the result. In the current investigation the Strouhal number based on the average flow conditions across the cell was approximately 0.20. Therefore the use of a strip theory can never produce local errors greater than the difference between the average conditions of the cell and the local conditions at the cell boundary.

Accomplishments:

1. Different shedding modes were found in the near wake flow behind a bluff body with mildly imposed three-dimensionality. Whether the three-dimensionality be introduced be a 2-D splitter plate, a splitter plate with a periodic trailing edge, body taper or a linearly varying incoming flow vortex dislocations were found to be a fundamental common feature in the flow for all of these configurations

2. It was found that the introduction of mild geometric three-dimensionality can control the positions of vortex dislocations.

3. Combined uniform shear and a uniformly tapered cylinder can produce a flow with a constant shedding frequency in the near wake.

4. For a mild three-dimensionality in the flow a two-dimensional strip theory approach appears to be valid.

Publications from ONR sponsored work

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