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Vortex shedding characteristics of the wake of a thin flat plate with a circular trailing edge

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A B S T R A C T

The near and very near wake of a thin flat plate with a circular trailing edge are investigated with direct numerical simulations (DNS). Data obtained for two different Reynolds numbers (based on plate thickness, D) are the main focus of this study. The separating boundary layers are turbulent in both cases. An earlier investigation of one of the cases (Case F) showed shed vortices in the wake that were about 1.0D to 4.0D in spanwise length. Considerable variation in both the strength and frequency of these shed vortices was observed. One objective of the present investigation is to determine the important contributors to this variability in strength and frequency of shed vortices and their finite spanwise extent. Analysis of the data shows that streamwise vortices in the separating boundary layer play an important role in strengthening/weakening of the shed vortices and that high/low-speed streaks in the boundary layer are important contributors to variability in shedding frequency. Both these features of the boundary layer contribute to the finite extent of the vortices in the spanwise direction. The second plate DNS (Case G, with 40% of the plate thickness of Case F) shows that while shedding intensity is weaker than obtained in Case F, many of the wake features are similar to that of Case F. This is important in understanding the path to the wake of the thin plate with a sharp trailing edge where shedding is absent. Here we also test the efficacy of a functional relationship between the shedding frequency and the Reynolds numbers based on the boundary layer momentum thickness (Re_θ) and D (Re_D); data for developing this behavioral model is from Cases F & G and five earlier DNSs of the flat plate wake.

1. Introduction

The wake of the thin flat plate with a sharp trailing edge and turbulent boundary layers has been discussed in several articles, one of the earliest being that of Chevray and Kovasznay (1969). The ratio of the boundary layer momentum thickness to the trailing edge thickness of the plate (θ/D) is large (23.2) in their study. Profiles of measured mean velocity and turbulent normal intensities and shear stress are provided. The boundary layers merge gradually to form the wake. Large-scale vortex shedding is absent. Other notable experimental investigations of the thin flat plate with a sharp trailing edge include those of Ramaprian et al. (1982), Nakayama and Liu (1990), Hayakawa and Iida (1992) and Thomas and Liu (2004). In addition to the experimental investigations mentioned above analytical solutions based on certain simplifying assumptions are provided by Alber (1980). In this study the centerline velocity distribution in the streamwise direction (x) in a region of the near wake is approximated by a logarithmic relation similar in form to that obtained for the turbulent boundary layer upstream of the wake in these cases. A good comparison is obtained between experimental data and the 'wake log-law' in the near wake. Andreopoulos and Bradshaw (1980) observed this logarithmic behavior of the mean velocity in the near wake as well in their experimental data. They also comment that the data of Chevray and Kovasznay (1969) seem to follow a similar trend. A more detailed review of some of these articles is provided in Rai (2017).

In contrast to the thin plate with a sharp trailing edge, the thick plate with a blunt trailing edge (small θ/D) exhibits vigorous vortex shedding. Unlike the case of the cylinder, the Reynolds number based on momentum thickness of the boundary layer just upstream of the trailing edge (Re_θ) and the Reynolds number defined using the thickness of the flat plate or the diameter of its trailing edge (Re_D), are independent parameters. A detailed investigation of the wake of the thick flat plate with a circular trailing edge and *turbulent separating boundary layers,* was initiated by Rai (2013, 2014, 2015). This was accomplished with the aid of direct numerical simulations (DNS). The boundary layers as well as the wake were computed via DNS in these investigations. The separating boundary layers are fully turbulent well upstream of the trailing edge and are statistically identical. Thus the wake is symmetric in the mean.

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Collectively, the articles by Rai (2013, 2014, 2015) address several aspects of flat plate wake flow. The more important ones are briefly noted here. The distributions of phase-averaged turbulent intensity and shear stress (random component) in the near and very near wakes are provided. A new event-based phase-averaging procedure is introduced. Important flow features such as rib vortices and their structure and strength in relation to the shed vortices and evolution in time and the internal structure of braids & shed vortices are investigated. The relative importance of phase-averaged and fluctuating strain rates in the production of turbulent vorticity in the braids and cores is also investigated. Similar to the shear-layer instability that manifests in the case of the cylinder (see for example, Bloor, 1964, Prasad and Williamson, 1997, Kim and Choi, 2001 and Rai, 2010) with laminar separating boundary layers it was found that the flat plate wake also exhibits shear layer instability followed by the formation of shear layer vortices that have a profound impact on the structure of the shear layer and the formation of the shed vortices. The role of recirculation region vortices and log-layer eddies in generating the shear-layer vortices associated with this instability was investigated and established. It was found that shear-layer vortex generation rates vary as much as a factor of two from event to event. An analysis of velocity fluctuations in the upstream boundary layer indicated that high-speed streaks near the trailing edge result in higher shear-layer vortex generation rates. The existence of regions of isolated reverse flow that are disconnected from the main body of reverse flow in the trailing edge region was discovered and reported in Rai (2014). These regions are a result of powerful rib vortices that are formed in the high-strain-rate region that exists between the shed vortices in their initial state.

The role that entrainment plays in the case of the near wake of a thick flat plate is quite different than it does in the case of the far wake. Only a small fraction of the separating turbulent boundary layer forms the detached shear layer (DSL) and participates in the initial roll-up into the shed vortex. The log-layer eddies of the boundary layer travel past the trailing edge largely unaltered. It was determined that for some distance downstream, the wake with its shed vortices, ingests fluid that was originally part of the turbulent boundary layer. The log-layer eddies are assimilated in this process and become a part of the shed vortices and the braids. The effect of increasing θ/D on assimilation/entrainment was also investigated in this article; it showed that wakes with larger θ/D values continue to assimilate boundary layer fluid for longer (until a larger value of x/D); the important contributors to this effect are identified.

The objective of the more recent investigation by Rai (2017) is to better understand the changes in the characteristics of the wake of a flat plate with turbulent separating boundary layers (in particular changes in shedding and related wake features), as the plate becomes thin in *relation* to the boundary layer thickness (increasing θ/D). The trailing edge of the plate *remains circular* in the cases investigated in Rai (2017). Thus the wake flow is different from those obtained in the experimental investigations with sharp trailing edges that were mentioned earlier. Changes obtained with increasing θ/D in the coherence of the shed vortices (in the spanwise direction), roll-up of the detached shear layers, the basic shedding mechanism (initiation of circulation), substantial variation in shedding frequency for the case with the largest value of θ/D, centerline velocity spectra, and time-averaged velocity statistics are discussed in this article. Some of the reasons underlying the substantial changes in the observed flow features as θ/D is increased are provided.

The four cases investigated in Rai (2017) are labeled Cases A, D, E & F. Case A is considered the reference case. Values of Re_D and the ratio $\psi = (\theta/D)/(\theta/D)_{Case\ A}$ for the different cases are provided in Table 1. The ratio ψ is essential in comparing the value of (θ/D) for any given case to that of the reference case (Case A); it varies substantially over the cases considered (by a factor of 20.43). Table 1 also provides the value of ψ for the case computed during the present investigation, Case G. The Reynolds number based on plate length L is the same in all cases, $Re_L = 1.25 \times 10^6$.

Table 1
The parameters Re_D and ψ for Cases A, D, E, F (Rai, 2017) and G.

	Re_D	ψ
Case A	10,000	1.00
Case D	5000	2.28
Case E	2500	4.89
Case F	625	20.43
Case G	250	51.59

One of the findings of Rai (2017) is the loss of coherence in the spanwise structure of the shed vortices as θ/D is increased. In Case A the shed vortices are clearly observed as nearly cylindrical regions of low pressure (Fig. 6a in Rai 2017). They show little distortion in the z direction. Shed vortices that are ruptured or that show large distortions are rare in Case A. Case D shows larger spanwise distortions near the base region (in comparison to Case A, Fig. 6b in Rai 2017). Case D also shows what appears to be the beginning of vortex breakdown further downstream. Thus we have less structured shedding as θ/D increases by a factor of 2.28. Case E (Fig. 6c in Rai 2017, which involves a further increase of θ/D) yields significant vortex distortion in the entire near-wake region. Clearly, increasing θ/D beyond a certain level results in the loss of coherence of shed vortices.

Contours of instantaneous spanwise vorticity in a (x, y) plane for Cases A and E are compared in Rai (2017) to better understand the loss in coherence with increasing θ/D. As mentioned in Rai (2014), the shed vortex at inception in Case A is not a single cylindrical vortex as in low Reynolds number cylinder flows. Instead, it is an amalgam of several smaller vortices of both signs. Vortices of the same sign as the vorticity in the shear layer that is rolling up are dominant. Segments of the shear layer and shear-layer vortices are incorporated in the newly forming vortex. The comparison in Rai (2017) showed that the differences between Cases A & E are striking. Firstly, relative to the thickness of the plate, the thickness of the DSL in Case E is considerably larger than in Case A. Secondly, much of the small-scale activity seen in Case A is absent in Case E. The third and perhaps the most important difference is that the two DSLs in Case E are separated by a physical distance that is approximately one quarter of that in Case A (the trailing edge diameter in Case E is 0.25 times that in Case A). The smaller separation results in a stronger interaction between the DSLs in Case E. There is less room for a more conventional, approximately circular, roll-up of the DSLs. Instead, often a folding of the DSL into two distinct layers occurs in Case E. The resulting shed vortex is initially stretched out in the x direction and sometimes breaks up into multiple shed vortices that occasionally reconstitute into a single larger shed vortex.

The increases in θ/D in cases D and E in comparison to Case A (increase in ψ) resulted in the initiation of deterioration in the shedding process. In Case F, where ψ is large (20.43), the observed shedding characteristics are significantly different from the earlier cases. Sequences of approximately spanwise vortices, between 1.0D & 4.0D in length, were observed (Fig. 13 in Rai 2017). While several sequences show vortices well aligned with the z direction some of the vortices are approximately aligned with the x direction. In the trailing edge region many of them are nearly streamwise vortices from the upstream boundary layers. The two most significant features observed were a) the spanwise vortices are of finite length in the z direction and b) the sequences in time are finite. If indeed the sequences comprise shed vortices, then *shedding seems to be intermittent in Case F*. Some of the questions that arise are as follows: Is the shedding process similar to the more conventional shedding of Cases A & D? What is the cause of the observed intermittency in shedding? What causes the shed vortices to be of finite length? How does the spectrum obtained for the cross-stream velocity in Case F compare with that of Case D at the wake center-plane? Does the spectrum have a sharp peak? How do the fluctuations in velocity compare in the two cases? As demonstrated in Rai (2017), Case F does exhibit *continuous vortex shedding* although the