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Observations on the Honji instability

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ABSTRACT

A numerical investigation of three-dimensional sinusoidally oscillating flow around an infinitely long cylinder was conducted to examine the onset of the Honji instability and to gain insight into the mechanism that causes the Honji instability to arise. An attempt is made to quantify when the instability occurs using the dimensionless flow parameters of the Keulegan–Carpenter number (KC) and the Sarpkaya number (β). Through numerical analysis and an explanation of physics, it is shown that the Honji instability occurs through the mechanisms described by Lord Rayleigh, but is significantly different from the Taylor, Dean, and Görtler instabilities.

1. Introduction

The renewed interest in the study of the characteristics of periodic flow past bluff bodies, and the circular cylinder in particular, was prompted when Sarpkaya (1976) suggested that force coefficients obtained at low Reynolds Numbers may not be scalable to higher Reynolds Numbers. The direct relevance to the offshore industry for these kinds of flows and the need for predicting the forces resulting from fluid–structure interactions has led to several experimental and computational studies. A pivotal moment came when Honji (1981) observed three-dimensional spanwise structures induced by the flow. Honji oscillated a cylinder in a water tank with values of the Sarpkaya number (also known as the frequency parameter), (β) in the range, $\sim 70 < \beta < \sim 700$ and values of the Keulegan–Carpenter number (KC) up to about 4. In this context, $\beta = f D^2/\nu$ and $\mathrm{KC} = U_m T/D$, where D is the cylinder diameter, T is the oscillatory period, $f = 1/T$ is the frequency of the oscillation, U_m is the maximum freestream velocity, and ν is the fluid kinematic viscosity. Honji showed that, depending on the value of β, the induced flow remained two-dimensional for KC less than 1.2–2.4. As KC was increased, the induced flow began to exhibit a marked three-dimensional mushroom-like structure due to instability in the flow. The mushroom-like structures, or paired vortices of opposite sign, are formed on the cylinder wall perpendicular to the direction of oscillation and have an equidistant spacing, λ in the axial direction and arrange themselves alternately in a vertical double row in a plane normal to the direction of oscillation. Honji did not give a name to the three-dimensional instability, but noted that it seemed to be a kind of centrifugal instability.

Based on Honji's (1981) investigation, Hall (1984) conducted a linear stability analysis for the limiting case of very small KC and very large β in a two-dimensional streaming flow. The Sarpkaya number was taken to be large so that the unsteady boundary layer on the cylinder was small compared with its diameter. Hall was able to obtain a relationship

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between KC and β,

$$\mathrm{KC_H} = 5.778\,\beta^{-1/4}(1+0.205\beta^{1/4}+\ldots), \tag{1}$$

which agreed with Honji's data. Hall asserted that the instability observed by Honji is of the Taylor–Görtler type.

Sarpkaya (1986) conducted an extensive experimental investigation of the force coefficients and how they are affected by the Honji instability, separation, and transition to turbulence. Sarpkaya pointed out that there were several significant differences between the Taylor–Görtler instability and the instability associated with oscillating flow around the cylinder; he proposed calling it the "Honji instability". As KC increases above the Hall Line, i.e., Eq. (1), the flow becomes unstable to axially periodic vortices (the mushroom-like structures), which leads to separation, vortex shedding, and eventually to a minimum drag force. For a given β value, the differences in the KC number where separation, minimum drag, and turbulence are very small and difficult to measure without notable uncertainty. The effect of transition to turbulence on the variation of C_D is not as drastic as that of the Honji instability.

Hara and Mei (1990a,b), in their studies of oscillating flows over periodic ripples, generalized Hall's analysis for oscillating flow over other convex surfaces. Following Hall, they made a first-order approximation to $\mathrm{KC_H}$,

$$\mathrm{KC_H}\beta^{1/4} = 5.778, \tag{2}$$

and then noted a relationship to the critical Taylor number (Ta), which is a ratio of the centrifugal force to the viscous force,

$$\mathrm{Ta} = \mathrm{KC}\beta^{1/4}. \tag{3}$$

Hara and Mei showed that there exists a local Taylor number,

$$\mathrm{Ta} = A^2/R\delta, \tag{4}$$

where A is the oscillatory amplitude and δ is proportional to the boundary layer thickness, and they also showed that an instability of the centrifugal type could occur in a two-dimensional flow when the local Taylor number exceeds a certain threshold ($\mathrm{Ta_{cr}}$). In their analysis of periodic ripples, they assumed that the boundary layer thickness was small and constant and the local radius of curvature, R, varied. For flow around a cylinder, R is fixed and the local boundary layer thickness, δ, varies as illustrated through the use of vorticity contour plots in Suthon and Dalton (2011). The time τ in this paper refers to the time in a given oscillatory cycle and not to the elapsed time since the calculation started.

Sarpkaya (2002) continued his previous investigation by conducting experiments for $0.02 < \mathrm{KC} < 1.0$ and $10^3 < \beta < 1.4 \times 10^6$. He divided the KC–$\beta$ plane into three regions as shown in Fig. 2. The region on the left where $\mathrm{KC} < \mathrm{KC_S}$ is a region in which there are no observable structures or those that are created do not survive the half-cycle in which they were created. The flow is considered two-dimensional based on observations of the flow using laser-induced fluorescence visualization. The unstable transition region in the middle, $\mathrm{KC_S} < \mathrm{KC} < \mathrm{KC_H}$, is where quasi-coherent structures are formed from dipole tubes and eventually become mushroom-shaped structures at the Hall Line. The region on the right where $\mathrm{KC} > \mathrm{KC_H}$ is a region where the mushroom-shaped coherent structures undergo complex chaotic interactions, which leads to separation and turbulence. Based on the observed data, Sarpkaya plotted the Stability Line as

$$\mathrm{KC_s}\beta^{2/5} = 12.5, \tag{5}$$

and linearized the Hall Line to a first-order approximation as

$$\mathrm{KC_H}\beta^{1/4} = 5.78. \tag{6}$$

Sarpkaya emphasized that the demarcation lines at $\mathrm{KC_S}$ and $\mathrm{KC_H}$ are not sharp and should be regarded as "fuzzy regions" due to the differences in the observer's ability to distinguish the onset of three-dimensionality and the variations in the quasi-coherent structures.

Elston et al. (2006) used Floquet analysis and direct numerical simulation to investigate oscillatory flow at KC less than 10 and β less than 100. This is the region in Fig. 2 where the Stability and Hall Lines cross, so that, for increasing KC,

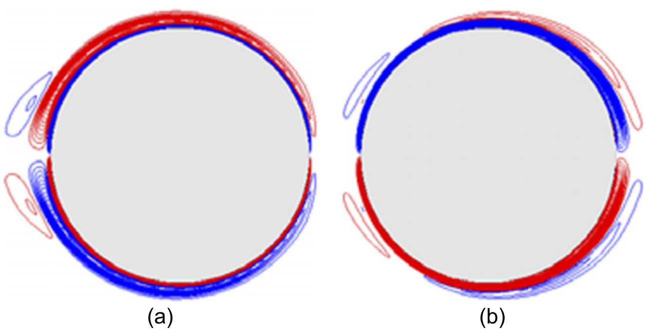

Fig. 1. Contour plots of axial vorticity with $\beta=1035$ and KC=1.5 at (a) zero mean flow, $\tau=0.00$; and (b) maximum mean flow, $\tau=0.25$.