Harmonic frequency analysis in turbulent double-cavity flow

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Abstract. Flow structure in a turbulent double-cavity flow was reported previously by Goltsman et al. (Physics of Fluids (2019) 31:6) as part I. The results of harmonic frequency analysis of the flow regimes in double symmetric cavities for a wide range of shape factor and Reynolds number based on the cavity length were obtained experimentally and numerically. The frequencies and amplitudes of the main harmonics of the oscillogram were determined; the fields of the Strouhal number and the relative amplitudes of the main harmonic were presented.

1. Introduction

Owing to generated self-sustaining oscillations, flows past cavities are of great practical and academic interest, and have been widely studied experimentally, numerically, and also theoretically. Double-cavity flow occurs in a plane-parallel channel with sudden expansion and subsequent sudden contraction with the presence of symmetric cavities located opposite each other at a certain distance between them. Examples may be found both in organic and technical systems. Therefore, the double-cavity flow is of interest for a wide range of fields.

In addition to the hydrodynamic flow pattern past the double symmetric cavities, the frequency-harmonic analysis is also of interest. In the paper of [1], flows in symmetric double cavities for sufficiently small 3666<Re_L<8330 via hot-wire measurements were studied. Figure 1 shows that the measurements by a hot-wire anemometer were performed only at eight points (P1-P8). Studies of [1] showed that only velocity oscillograms at P2 and P4 points are interesting for spectral analysis, since they provide information from both the shear layer and the recirculation region.

Figure 1. Measurement points of velocity oscillograms in [1]
As in the case of point measurements of the velocity oscillograms, the field optical method allows one to obtain the spectra of turbulent pulsations; moreover, it is possible to acquire two-dimensional fields of frequency-harmonic characteristics. The present paper as a logical extension of the article by [2] as part I employs the SIV optical technique in order to conduct harmonic frequency analysis of the flow regimes of double symmetric cavities. The results of experimental and numerical studies in double symmetric cavities of finite length for a wide range of dynamic similarity numbers of shape factor (SK) and ReL (ReL=UL/ν is Reynolds number based on the cavity length L and average flow rate U in the channel in front of the cavities) were obtained.

2. General procedure

2.1. Experimental study

Flow pattern of double-cavity flow has been studied experimentally by means of smoke image velocimetry (SIV) [2] in the range of 3900<ReL<46000. The test section was a 1.3-m long 115×150 mm² rectangular channel with a smooth inlet and a contraction of 6:1. There were inserts with a height of D=35 mm and a width of S=150 mm installed inside the channel. 1000-mm-long inserts were located directly after the inlet of rectangular test section and were rigidly fixed. The 300-mm-long inserts were located at a distance of L from the fixed inserts and were movable in the streamwise direction; it made possible to adjust the cavity length. The flow pattern in the channel symmetry plane at the distance of L=1 m from the test section inlet was recorded by a monochrome high-speed camera Fastec HiSpec with the frame resolution of 180×600 pixel at L=35 mm and 1005×600 pixel at L=210 mm (scaling factor of 0.2 mm/pixel), frame rate of up to f=739 1/s.

Flow velocity fields were measured by the optical SIV technique based on digital processing of flow pattern video recordings. When conducting harmonic frequency analysis, to reduce the random errors, 16×16 pixel interrogation windows were considered.

2.2. Numerical study

ANSYS Fluent 19.2 software was used. Double-cavity flow was described by Reynolds-averaged Navier-Stokes equations with anisotropic Reynolds stress model. The 3D CFD (Computational Fluid Dynamics) geometric model was completely identical to the channel of the experimental setup, except that the uniformity of the inlet velocity profile was provided by the boundary condition, and not by the smooth inlet. The hexahedral computational grid was generated in ANSYS Meshing. During the calculation process, the grid was adapted to achieve a maximum size of the wall cells of not more than 5y⁺ in ANSYS Fluent. After adaptation, the number of nodes was about 3-4 million.

3. Results and discussion

Here we provide a brief description of the previously obtained results [2]. As published in [2], we proposed to distinguish three flow regimes in a turbulent double-cavity flow:

I. Jet-like flow (SK<2, ReL>5000). In this flow regime, the velocity profile in the flow core is almost self-similar along the surface of the cavities; therefore no more than 5% of the flow mass enters the cavity. The constancy of the flow velocity profile over the cavities leads to insignificant hydraulic losses in the section with a symmetric double cavity.

II. Underexpanded jet-like flow (2<SK<5, ReL>12000). The cavity length in this regime is sufficient to initialize the process of flow deceleration and expansion of the flow into the cavities; however, the flow attachment point to the bottom of the cavities is absent. From 5 to 20% of the flow mass passing over the cavities penetrates into the cavities.

III. Jet-like flow with attachment point (7<SK, ReL<12000). With increasing SK or decreasing ReL, a regime with an attachment point at the bottom of the cavity arises, which indicates the appearance of a cross section with extremely positive velocity vectors along the X-axis direction. This regime is
closer to the flow in the channel with a sudden expansion, a straight elongate section of constant cross section, and a sudden contraction than to the double-cavity flow.

Within this study, an attempt to obtain fields of Strouhal numbers \( (Sh=\frac{fL}{U}) \) and to determine areas with the maximum amplitude of velocity pulsations was made.

A fast Fourier transform was applied to each set of instantaneous velocity measurements in the point array (1)

\[
U(t) = A_0 + \sum_{n=1}^{\infty} \left[ A_n \cos\left(\frac{n2\pi}{T}t\right) + B_n \sin\left(\frac{n2\pi}{T}t\right) \right] \tag{1}
\]

Then, at each point, the \( f \) frequencies with the \( A_U \) maximum amplitude (2) were determined and fields of \( Sh=\frac{fL}{U_D} \) (Fig. 2 a), c), e)) and \( A_U/U_D \) (Fig 2 b) d), f)) were obtained (\( U_D \) is the average flow velocity before the cavities).

\[
A_U = \sqrt{A_f^2 + B_f^2}. \tag{2}
\]

**Figure 2.** Left: fields of the Sh number calculated from the frequency of local main harmonic; right: fields of local relative amplitude of the main harmonic pulsations. Top row: CFD data; bottom row: SIV results.
As it is known, if Sh<<1, the flow is approximately considered as steady or quasi-steady. If Sh>>1, there is a significant unsteadiness of the process.

For all three considered flow regimes, the thesis from [1] on the local extremum of the frequency-amplitude characteristic in the region of the P2 point is confirmed. In this region, both the Sh number and the amplitude of the pulsations increase. Also, figure shows one more similar region symmetrically located near the edge of the cavities.

According to the present study, all three regimes are steady, and the flow in the cavities is symmetrical. The values of the Sh number do not exceed 0.3. However, there are local areas where Sh is close to or greater than 1, this is especially characteristic of III regime. However, the turbulent energy generated in these regions due to turbulent diffusion transfer dissipates rather quickly.

For I regime, where a jet flows around cavities, the processes affecting the flow stability are concentrated in the region above the cavity: in the area of contact between the shear layer and the cavities. The relative amplitude of the main harmonics in the cavity is practically comparable to zero and does not exceed 0.03. The field of the Sh number is almost uniform and is characterized by small values.

When there is the underexpanded jet-like flow past the cavities (II Regime), as the jet expands and penetrates into the cavity, the region with increased values of Sh and relative amplitude also shifts and locates along the expanding jet boundary. This, in turn, increases the amplitude of the velocity pulsations in the cavities. The field of the Sh number almost becomes strongly non-uniform.

When the jet attaches the bottom wall of the cavity, there is more significant effect of the flow on the occurrence of disturbances. In the region of the flow attachment point, a large area with relative amplitude of pulsations of about 0.3 arises, which does not occupy the entire cavity in height, but also affects the flow above the cavity. In contrast to II regime, the field of the Sh number becomes uniform again with a value of the order of 0.2.

Conclusions
When applying the fast Fourier transform to the experimentally measured oscillograms of the instantaneous velocity, a harmonic frequency analysis of the flow regimes of double symmetric cavities was performed. For each oscillogram, the frequencies and amplitudes of the main harmonics were determined; using these data, the fields of the Strouhal number (Sh) and the relative amplitudes of the main harmonic of the oscillogram were plotted for the first time. The frequency-harmonic pattern of flow past the cavities agrees well with the observed steady flow pattern; the average value of Sh in the cavities is less than 1, and the relative amplitude depending on the regime does not exceed 0.3. Also, owing to the obtained characteristic fields for each regime, it was possible to identify the characteristic distributions and local extremes of the Sh number and relative amplitude, which is undoubtedly relevant information for the subsequent deeper analysis.

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