EXPERIMENTAL INVESTIGATION OF THE FLOW FIELD BETWEEN TWO OPPOSED DELTA WINGS

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Abstract: *This work discusses the flow features past a passive flow control device that is composed of two delta wings. The delta wings are situated in a way that they produce opposite lift forces. Major portion of the lift force is generated by the so called leading edge vortices that are special characteristics of delta wings. These vortices are characterized by high vorticity, thus they induce a velocity field of significant velocities. The authors expect that this device can be efficiently used as a part of industrial systems. In this paper the results of flow visualization are shown in detail.*

Keywords: *delta wings, flow visualization, vortex generator*

1. INTRODUCTION

When an isosceles triangle is placed into a flow in a certain angle of attack, they produce a characteristic, lift producing flow field. The basic principle can be seen on *Fig.1(a)*: the boundary layer on the pressure side flows outwards, and after reaching the leading edge it separates and becomes a free shear layer. This free shear layer is curled back towards the suction side of the wing because of the existing pressure difference, finally rolling up into a core of high vorticity. The vortex-induced velocity field and the free stream velocity into which the wing is placed will together end up in a spiralling velocity field around and along the axis of the vortex core, symmetrically on both sides of the delta wing [1]. Two characteristic features of the vortex core is the core sweep angle (Λ_{Core}) (*Fig.1(b)*) and the inclination angle of the vortex trajectory relative to the surface of the delta wing (β_{Core}) (*Fig.1(c)*).

However, delta wings were already used during World War II., and have been examined exhaustively since then, they are still present in today's scientific literature. The review article of Gursul et al. [2] gives a good overall idea of the present state of delta wing research, both in the exprimental and numerical field. Konrath and Klein [3] focus on using advanced flow measurement techniques, such as particle image velocimetry (PIV) or pressure sensitive paint (PSP) to have a more detailed insight to the flow topology above the delta wing. Other papers, such as Williamson et al. [4] and Menke et al. [5] concentrate rather on the unsteady nature of vortex formation and vortex breakdown. Of course, there are also several papers approaching the topic with CFD tools, like Raymond et al. [6] and Chen et al. [7]. The common in the above mentioned articles is that they are mostly aviation or military based. Godard and

Stanislas [8] gives an insight in the use of delta wings as flow control elements. *Fig.2* shows the concept, how 'half' delta wings can be used to energize the boundary layer and thus prevent the flow from separation.

The objective of the present paper is to qualitatively investigate the flow field above two delta wings opposed to each other in a way that they produce lift in opposite directions. Presence- or the absence of interaction of the flow fields are expected to be found.

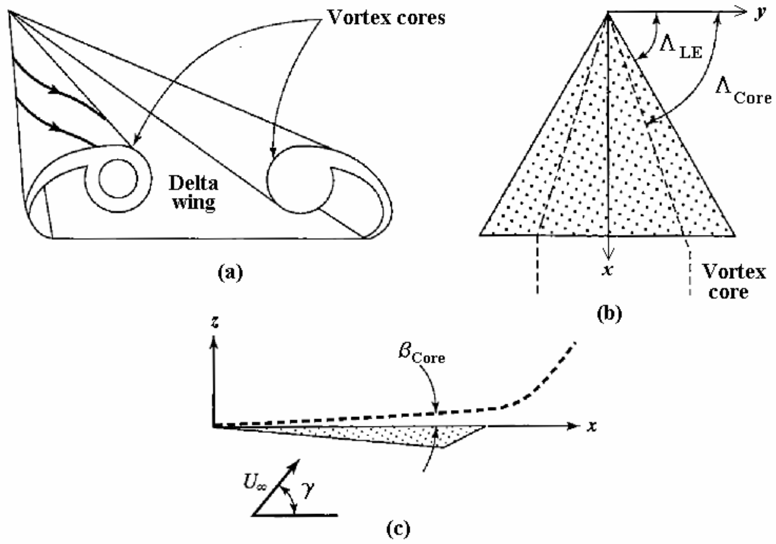

Fig.1. The structure of the flow field past a triangle; a) the overall vortex structure; b) representation of the core sweep angle; c) representation of the core inclination angle [1]

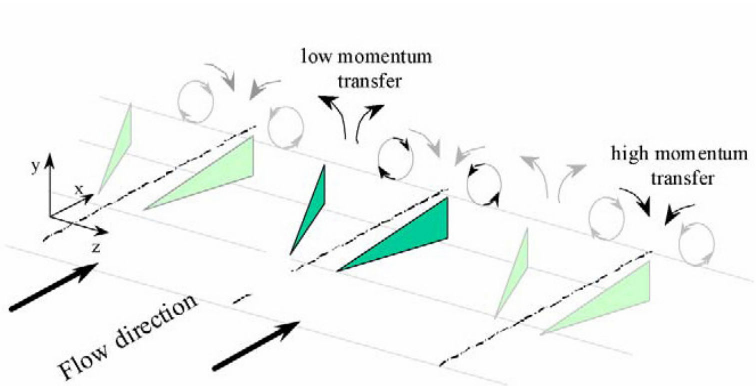

Fig.2. Triangles used as vortex generators to refresh boundary layer flows [8]

2. EXPERIMENTAL SETUP

A sketch of the experimental setup is shown in *Fig.3*. Two isosceles triangles: delta wings were placed in a vertical wind tunnel, in a way described in the introduction. The flow was moving in the z-direction, the normal direction was the *x*-direction, the spanwise direction was the *y*-direction. The material of the delta wings was a 2mm thick metal sheet, without any modification of the leading edge. The delta wings had a base of 152mm and a sweep angle of $\Lambda_{LE}=67.5°$. The distance between them was characterized by the distance of the tips, which could be set by moving the fixing rods along the *x*-axis. The angle of the delta wings with respect to the vertical could be set by rotating the fixing rods around the *y*-axis.

For the flow visualization oil fog, a laser sheet and a PCO type CCD camera were used. The oil fog was introduced into the test section with the help of a tube, upstream of the delta wings, far enough not to disturb the vortex formation. The laser sheet, forming a z-normal plane was mounted on a stand at the side of the wind tunnel, allowing continuous positioning along the z-axis. The camera was placed exactly above the two delta wings, far enough not to disturb the flow around the delta wings. It was set to take 8 bit images with a resolution of 640x480 pixels.

The wind tunnel used for the measurements was the vertical wind tunnel of the Theodore von Karman Wind Tunnel Laboratory at the Department of Fluid Mechanics, Budapest University of Technology and Economics. It is an open test section, recirculation wind tunnel, with a test section diameter of 1.42 meters. The velocity of the flow was chosen to be small enough for capturing well visible structures on the images.

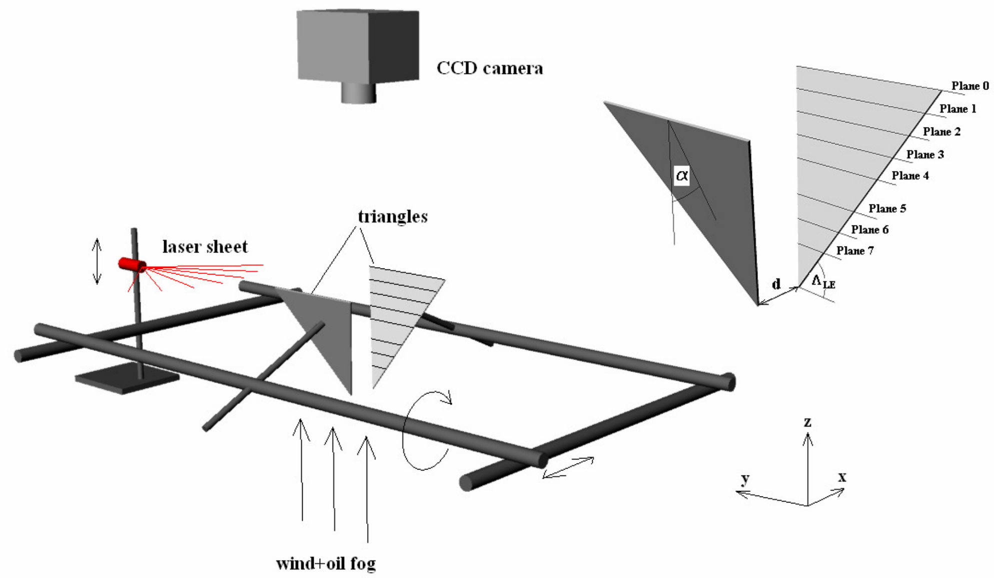

Fig.3. The test section arrangement and the investigated configurations and positions of the laser sheet

3. THE INVESTIGATED CONFIGURATIONS

Due to the inviscid nature of the formation of longitudinal vortices [9], the Reynolds number only influences the evolution of the initially inviscid vortex core. In the present case, the structure of the flow was investigated at only one Reynolds number which was $Re=101000$, based on the base length of the delta wing.

For the measurements two parameters were changed, the distance d between the apexes of the delta wings and their angle α, relative to the symmetry plane of the arrangement. Experiments were carried out for three different angles: $\alpha=25°$, $15°$ and $10°$, and four different distances for each angles: $d=0mm$, $8mm$, $22mm$ and $36mm$ (always symmetrical cases) (*Fig.3*). The magnitudes of the angles were chosen in a way so that the vortex formation could already be visualized (minimum angle limit), but there would be surely no vortex breakdown (maximum angle limit). Considering the distances, the values were set in a way so that the interaction of the flow fields above the two opposite delta wings would become clear during the experiment.

For each configuration a maximum of seven horizontal (z-normal plane) cross sections of different heights were investigated. The exact positions of the laser sheet for the different heights were previously marked on the delta wings (*Fig.3*). The numbering of the planes starts with zero at the base of the delta wings and goes up to seven as we are approaching the tips of the delta wings (*–z* direction). The distance between each marker line is *20mm* in the plane of the triangle sheet, except for the 4th and 5th line, were the distance is *30mm* because of certain measurement limitations. Also, there were some configurations for which less then eight planes could be examined because of the same measurement limitations and also because of the different nature of vortex formation.

The vortices were visualized by oil fog, based on the first theorem of Helmholtz. Thus the oil fog particles are captured by the vortices, allowing us to see their formation, size and trajectory.

4. VISUALIZATION OF VORTEX CROSS SECTIONS

Fig.4 shows a series of images taken at $\alpha=25°$; $d=8mm$ experimental setup, at all eight horizontal cross sections (*Plane 0-Plane 7*). For processing the images, first a reference point was checked on every image at a neutral place (same for each image), where there was no vortex formation. It was found that the reference point had the same intensity for every image, which allowed us for the following process: the vortices at *Plane 0* were taken as a basis as it was found to be the less intense. The intensity close to the edge of the vortex was checked and taken as a limit for a high pass filter. Than all other images for the specified measurement configuration was filtered with the previously set limit. The filtered values were set to be zero, thus allowing us to see the vortices much clearly. Most of the times only one or two vortices could be caught on one image, so they had to be superimposed afterwards to be able to see all four vortices on the same image. The basic observations concluded from *Fig.4* can be summarized as follows:

(1) All four vortices are fully formed at every examined plane, non of them is suppressed because of the proximity of the facing delta wing. They are approximately of the same size and the vortex formation is symmetrical both to the *x-z* and *y-z* planes, as far as it can be concluded based on visual observation.

(2) On the images *Plane 0-Plane 3* an interesting phenomenon can be observed. There is a horizontal line connecting the two delta wings, which in 3D means a vertical plane. (These lines could be also observed in *Plane 4-Plane 7*, however they did not have sufficient intensity to appear on the images.) This simply means that air arriving from upstream enters into the vortices and the rest is smeared into a vertical plane. The parts that remained white on the images are all areas with fluid entrained from outside.

(3) The development of the vortices can be very easily followed from the leading edge towards the trailing edge. Close to the apex of the delta wings, the leading edge vortex cores are clearly visible, which indicates an almost inviscid vortex, characterized by high velocities close to its core region. At this phase the vortices are close to be potential. As we are approaching the trailing edge the vortex cores cannot be traced any more so evidently. The vortices loose their potential characteristics, the core becomes a rotating rigid body and the vortex becomes turbulent. The size of the induced velocity field is increasing continuously as advancing from the leading edge to the trailing edge.

(4) It can also be observed that the vortex cores are getting farther and farther from the surface of the delta wing as we are getting closer to the trailing edge, which observation agrees well with the literature. There was an attempt made to quantify this distance, however the results should be treated rather as qualitative, than quantitative data because of the great uncertainty resulting from the fact that the measurement technique used was visualization oriented. The emphasis is placed more on the comparison of the different setups than stating exact measurement values.

5. LOCALISATION OF VORTEX CORES

The distance between the vortex core and the surface of the delta wing in the *x-y* plane was determined for each measurement configuration at each observation plane for each vortex.

The vortices were named *vortex no.1-vortex no.4*. From the image, the coordinates of the vortex core and the coordinates of the delta wing surface could be read, by subtraction of the distance of the vortex core from the surface of the delta wing could be determined in pixels. To change it into millimetres, the reference was the length of the cross section of the delta wing at the actual measuring height, which was known in pixels and in millimetres as well.

The results can be seen in *Fig.4*, which shows the distance between the vortex core and the surface of the delta wing in the *x-y* plane for all four vortices, for the measurement configuration: $\alpha=25°$; $d=36mm$. It can be seen that all vortices start at approximately the same distance close to the leading edge, which distance becomes five times bigger at the trailing edge. It can also be observed that *vortex no.4* seems to diverge more, than the rest of the vortices. This is believed to happen due to certain asymmetries in the equipment.

The results of the other configurations are not shown here, however the former observations are valid for all of them. *Fig.5* shows the distance of the vortex core of *vortex no.1* from the delta wing surface for the different tip distances at $\alpha=25°$. It was previously expected that there would be some interaction between the vortices of the two opposite delta wings, but the measurement results show no sign of such an interaction for the measured interval, i.e. $10° \leq \alpha \leq 25°$.

This can happen because in reality there is no interaction, or the measurement device was not sensitive enough to discover it. In *Fig.6* the vortex core trajectory of *vortex no.2* appears for the different angle configurations at $d=36mm$. It can be seen that with increasing angle of attack, the angle between the delta wing surface and the line of the vortex core also increases, which observation is also supported by the relevant literature.

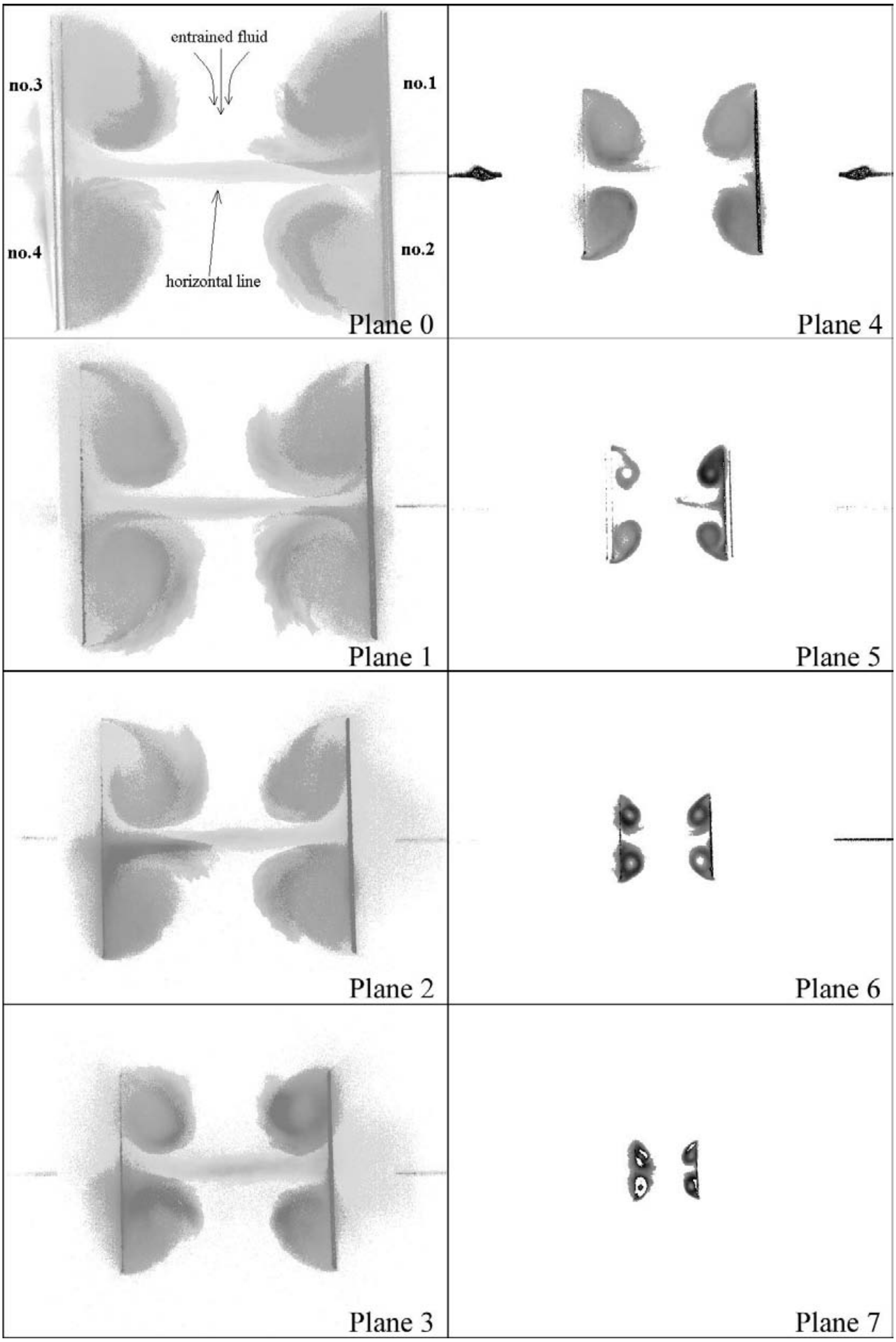

Fig.4. Horizontal cross sections of the vortices at *α=25°; d=8mm* measurement configuration

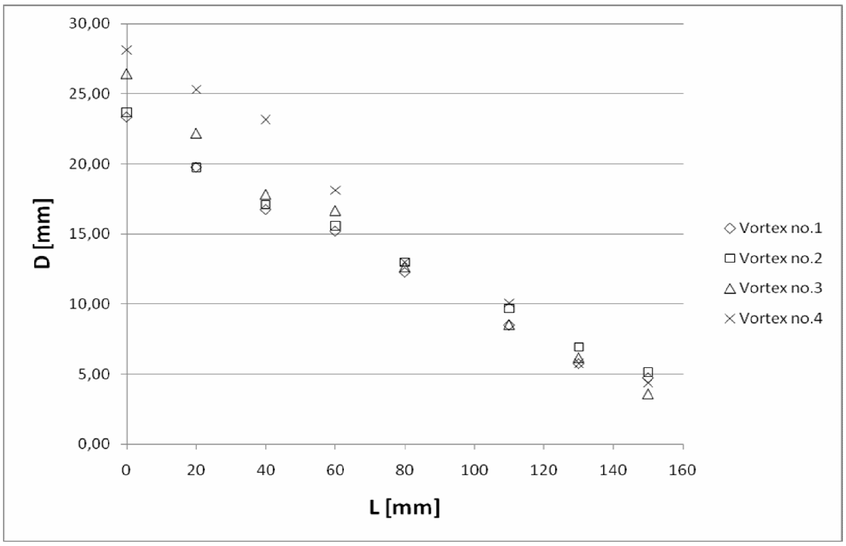

Fig.5. Distance between the vortex core of the individual vortices and the delta wing in the plane of the laser light for measurement configuration: *α=25°; d=36mm*

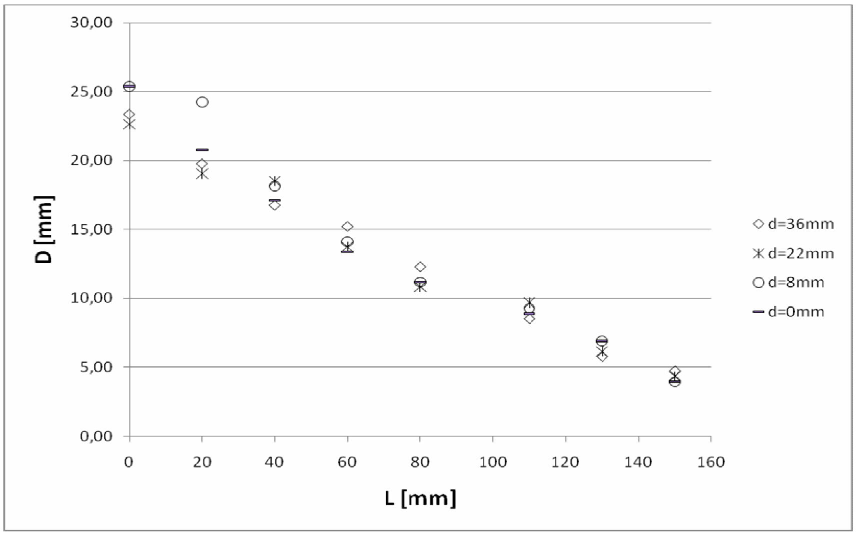

Fig.6. Distance between the core of *vortex no.1* and the delta wing in the plane of the laser light for the different tip distances at *α=25°*.

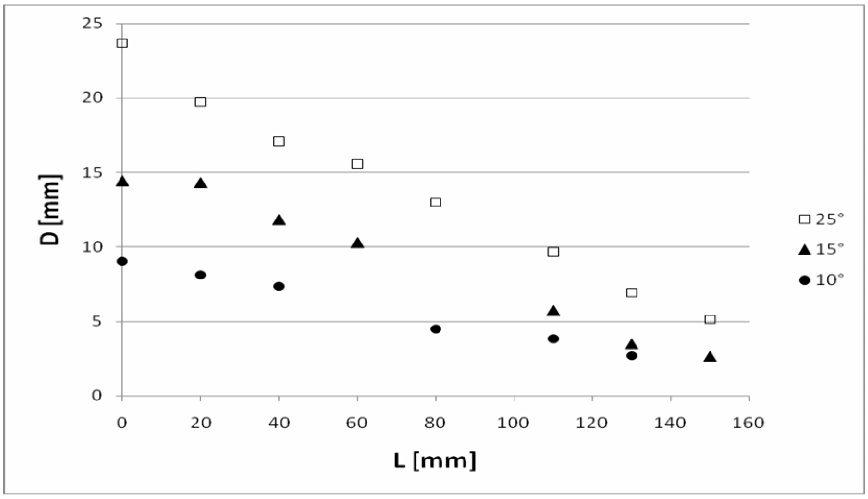

Fig.7. The vortex core trajectory of *vortex no.2* for the different angle setups at *d=36mm*

5. CONCLUSIONS

In the present paper the structure of the vortices over two opposed delta wings were characterized by means of flow visualization. The delta wings were set in symmetric configurations only. The angles of attack and the distance between the two apexes were varied. The overall structure of the flow field was determined by using laser sheets oriented perpendicularly to the flow direction and a CCD camera that photographed the cross sections of the vortices which were filled with oil fog. From the present investigation it was found that there was no visible interaction between the flow fields of the two delta wings for $10° \leq \alpha \leq 25°$, even in those cases when the apexes of them were in contact ($d=0mm$). It suggests that in symmetric arrangement the two delta wings can be handled independently from each other in the vicinity of the leading edges. The evolution of the vortices downstream from the trailing edges of the delta wings was not investigated.

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