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THE HORN - POLKEMMET

EXPERIMENTAL ASSESSMENT OF THE AERODYNAMIC RESPONSE CHARACTERISTICS

by

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SUMMARY

A qualitative assessment of the aerodynamic response characteristics of the Horn, planned for Polkemmet Country Park, West Lothian, is presented. The assessment is based on scale model experiments conducted in the smoke flow visualisation wind tunnel in the Department of Aerospace Engineering, University of Glasgow for a range of flow conditions compatible with the expected wind environment. A number of adverse unsteady aerodynamic phenomena are identified which are highly dependent on wind direction. These include a dominant transient vortex system emanating from the mouth of the Horn, periodic vortex shedding from the neck and support mast, conical vortices generated on the Horn surface, and a general bluff body wake in the lee of the Horn. It is anticipated that the aerodynamic behaviour identified in the model tests persists, at least qualitatively, under full scale conditions. As a result, the potential exists for both aerodynamically induced transient and periodic structural excitation of the Horn. Means of alleviating the adverse aerodynamic characteristics are available. However, any assessment of the effectiveness of such measures requires further experimental investigation.

CONTENTS

1. INTRODUCTION

Presented in this report are the results of a series of smoke flow visualisation tests carried out on a model of the "Horn of Plenty" to be erected in Polkemmet Country Park, West Lothian. The tests were commissioned by Crouch Hogg Waterman (CHW) consultants following the submission of a proposal by staff from the Department of Aerospace Engineering, University of Glasgow. Observations are made on the results obtained and a number of conclusions are drawn on the nature of the flow, including the influence of several potentially harmful coherent unsteady aerodynamic structures.

1.1. Background

Concerns over the flow regime around the proposed Horn of Plenty led CHW consultants to approach the Department of Aerospace Engineering at the University of Glasgow with a view to commissioning a series of investigative wind tunnel tests. The structure comprises a tall slender tapered tower of circular section which expands and moulds, at the top, into the shape of a horn (Figure 1.1). Of particular concern is the relatively large projected area and general configuration of the horn section at the top, and its susceptibility to harmful unsteady aerodynamic forcing. After consultation it was agreed that the best initial approach was to identify the most prominent aerodynamic forcing mechanisms from scale model tests using the Department's smoke flow visualisation wind tunnel. Any subsequent work deemed to be necessary; for example, the assessment of potential solutions, was to be the subject of a further proposal.

1.2. Programme of Study

To identify the unsteady aerodynamic behaviour exhibited by the Horn, a series of wind-tunnel tests was performed on a scale model of the structure for a range of on-coming wind-directions at a fixed nominal wind speed. To maximise the model dimensions in the vicinity of potentially critical regions such as the horn, neck and adjoining support mast, only the upper third of the structure was modelled. Flow patterns exposed by the wind-tunnel tests were then examined to assess the likelihood of adverse structural excitation. Consideration was then given to the persistence of the observed aerodynamic phenomena under full-scale conditions compatible with the expected wind environment. Possible means of alleviating adverse aerodynamic flow structures of the type identified were then addressed.

2. EXPERIMENTAL METHODOLOGY

Flow visualisation experiments on the Horn were carried out in the University of Glasgow smoke flow visualisation wind tunnel. This wind tunnel consists of a sealed room containing a 5.5m long, 0.91m by 0.91m square cross section tube. The upstream end of the tube is open to the atmosphere via a 9:1 contraction. Air is sucked down the tube by a fan placed 1.5m away from the downstream end of the tube, and the air is vented back into the atmosphere through filters. The bottom and one side of the tube are built of plywood while the roof and other side are made of perspex to allow illumination and viewing of the flow patterns. The wind tunnel is illustrated in Figure 2.1.

The model tested was a 17.5:1 scale representation of the top third of the structure. This size was chosen with quality of flow visualisation in mind. The anticipated flow patterns dictated that smoke should be injected out of the model surface. Hence, the model needed to be of a hollow construction. To achieve this, fibre-glass and resin moulds were formed from a handmade solid wooden cast of the model. Carbon fibre shells of each half of the model were then created from the moulds and the inside surface of the opening or mouth of the Horn was fabricated separately of carbon fibre and the three parts then bonded together. A resin plug was formed inside the bottom end of the model and an aluminium base plate was screwed into the resin plug. This base plate was designed so that when the model was mounted on the floor or wall of the wind tunnel the angle of the incident flow could be easily altered. A photograph of the model in the wind tunnel is presented in Figure 2.2 along with notation describing the various features of the Horn.

Preliminary investigations of the flow over the Horn were carried out with smoke injected into the air upstream of the model. The results of this flow visualisation allowed the positions of the smoke injection holes on the model surface to be determined. Holes of 1mm diameter were then drilled through the skin of the model - a ring of holes inside the opening or mouth of the horn, a ring of holes around the vertical stem and three rows of holes on one side of the curved neck with two of these rows extending to just behind the lip of the mouth. With the model in its chosen attitude the smoke flow was illuminated either by a laser sheet or a halogen flood light. Photography was performed using a high resolution monochrome CCD video camera and the flow patterns were recorded onto VHS videotape. Selected frames from the video sequences were then digitised and enhanced for presentation and analysis.

3. RESULTS OF WIND-TUNNEL TESTS

A number of specific flow phenomena were observed. These were highly dependent upon the direction of the oncoming flow to the model. The sign convention of the incident flow is shown in Figure 3.1. Descriptions of the flow phenomena are as follows.

3.1. Flow with Mouth of Horn into Wind

3.1.1. Flow Angles less than 40°

The most remarkable feature of the flow into the mouth at these low incidences was the formation of recirculation zones. These were formed during two distinct modes of the flow; the flow would be in one mode or the other for a long time, and could switch between either in a very short time. The manner of recirculation in each mode was of great consequence to the flow going into and out of the mouth.

The first recirculation mode observed tended to bring air into the upper portion of the mouth and expel it through the lower portion. Well organised vortex structures sitting inside the mouth of the horn acted to drive the air in the associated sense. A sequence of video stills showing this sense of flow is given in Figure 3.2. The centre-line of the model is at an angle of 20° to the oncoming flow. Illumination of the flow was provided here by the laser sheet. The view is into and to the side of the mouth, and the outline of the opening of the mouth has been superimposed. The recirculation zone is shown by the area of white smoke. At the top of the zone, a relatively energetic vortex was observed. The flow below the vortex was seen to be fairly quiescent. However, the air in the quiescent region would occasionally find its way out of the lower lip of the mouth; Figure 3.2c shows a smoke filament leaving the mouth.

Figure 3.3 shows a sequence of stills of the model viewed from the side. The flow leaving the lower portion of the mouth is indicated. A mass of air just ejected from the mouth is shown in Figure 3.3a, and Figure 3.3c shows this mass about to impinge on the stem.

In the second mode, the air entered the mouth through the lower portion of the mouth and was expelled through the upper portion. Consequently, the flow in the recirculation zone was of an opposite sense to the previously described mode. The recirculation zone was much more energetic than that described above and consisted of a single, larger vortex structure; the diameter of the zone was observed to be as much as one third of the height of the mouth. The vortex was often seen to persist for a long time, merely recirculating the air entering through the lower half of the mouth and driving air out of the mouth under the top lip. However, the vortex would occasionally move out of the mouth in a very dramatic fashion. Figure 3.4 shows a sequence of laser illuminated video stills showing the vortex leaving the mouth. In this figure the model centre-line is at 0° to the oncoming flow. The view is from the side, looking into the upper portion of the mouth. In Figure 3.4a and 3.4b the vortex is shown in its steady sense; the pictures have been annotated to show the entrained flow. In Figure 3.4c the vortex has moved slightly out of the mouth. As the vortex moves out and upwards it intensifies and the core of the vortex becomes smaller (Figure 3.4d). Once the vortex starts to move, the rate of movement out of the mouth becomes very large indeed; Figures 3.4d, e and f are separated by only 1/25s. The shrinking of the core of the vortex can also be seen in these pictures. The final three pictures show the vortex passing over the top lip and being washed away downstream. Once the vortex left the mouth the recirculation zone was observed to restart, often in the same sense.

An important feature of the above described phenomenon is the vortex intensification. As vortices intensify, the suction in the vortex core increases. Since the core pressure changes then the loads exerted on the structure will also change. The second mode showed no periodicity. The vortex was as likely to sit inside the mouth for a long time as it was to pop-out. The first flow mode, however, tended to exhibit a more definite periodicity of shedding of mass out of the mouth.

3.1.2. Flow Angles greater than 40°

As the model was rotated such that the opening of the mouth tended to be side-on to the approaching wind, the character of the flow changed dramatically. Once the model centre-line exceeded an angle of 40° to the oncoming flow the recirculation described in Section 3.1.1 ceased to exist, and the axis of recirculation inside the mouth changed from horizontal to vertical. This recirculation also sat much deeper inside the mouth than before. A floodlit and laser illuminated photograph of the flow at 50° incidence is shown in Figure 3.5. The view of the flow in this picture is from above the top of the model, looking into the mouth. The recirculation zone was seen to be quite energetic; incident flow was seen to hit the windward surface of the inside of the mouth, recirculate and then leave the cavity. The mean flow direction meant that the flow tended to leave the lower portion of the mouth. The recirculation was stable and persistent. Large masses of air were occasionally ejected from the mouth although no specific period was observed.

At larger angles of inclination (around 60°), the separated flow from the upstream lip buffeted the windward surface of the inside of the mouth. The recirculation zone at this incidence was still highly energetic, and the same overall features as the 50° case were seen. Above 70° inclination the recirculation zone inside the mouth was much less energetic than at the lower angles of incidence, and only a gentle swirling of the flow was observed.

At these high incidences the wake behind the Horn was evidently very large and highly disorganised, while a very large stagnation zone on the windward surface of the horn was seen. Of particular note was the acceleration of the flow through the gap between the side of the Horn and the sloped neck. Shown in Figures 3.6a and 3.6b are floodlit views from the top and behind the model of the flow with the model centre-line at 90° to the oncoming air. In Figure 3.6a the light patch of smoke indicated behind the centre of the model is the wake emanating from the stem of the model; thus a sense of the size of the wake off the Horn compared to that off the stem is gained. In this figure the outline of the windward surface of the Horn is also seen, which gives an impression of the size of the stagnation area ahead of the model. Figure 3.6b shows the wake of the model in the side on configuration viewed from behind. Again an impression of the size of the wake is gained.

3.2. Flow with Apex of Neck into Wind

The angle of the model centre-line to the oncoming flow is now in the range 140°-220°. The flow was observed to change drastically over a small range of flow angles, as described below. All the figures presented used laser illumination, with the plane of the laser sheet at right angles to the axis of the wind tunnel. The flow was viewed from behind. Hence, in the figures presented, the flow direction is out of the plane of the paper.

3.2.1. Apex of Neck directly into Wind

The inclination of the model centre-line is now at 180° to the oncoming flow. The horn itself produces a large wake which is relatively disorganised. The flow over the sloped part of the neck demonstrates regular, periodic vortex shedding however, and the shed vortices buffet against the lower surface of the horn. Figure 3.7 shows a sequence of pictures of the vortex shedding. The laser sheet was pointed into the gap between the horn and the sloped neck, and the view of the flow is from behind the model. The laser also illuminates the surfaces of the neck and the horn, so an impression of the distance of the flow structures from the nearby surfaces may be gained. The lower half of the first frame in the sequence (Figure 3.7a) shows a vortex about to be shed from the relevant side of the model. The following frames show that the vortex is very close to the horn and neck surfaces, indicating buffeting on the horn by the flow structures shed from the neck.

3.2.2. Apex of Neck 10° out of Wind

The inclination of the model centre-line is now 170° to the oncoming flow. It was immediately obvious from the visualisation that the level of *periodicity* observed above had been drastically suppressed. The reason for this appears to be the flow of the air through the gap between the sloped neck and the windward surface of the horn. Figure 3.8 shows a video still of the flow.

3.2.3. Apex of Neck greater than 10° out of Wind

With the apex of the neck still pointing into the wind, but with the model centre-line at even greater inclination to the oncoming flow, an additional flow phenomenon was observed. This consisted of a pair of vortices positioned over the lee side of the horn. The axes of the vortices lie along the generators of the horn surface. Figure 3.9 shows a sequence of three pictures of the flow with the model centre-line at 150° to the oncoming flow. The flow direction is out of the paper, and the view of the flow is from behind the model. Laser illuminated cross sections of the vortices can be seen. The vortex on the right of the figure is on the upper surface of the horn (i.e. facing away from the neck), while the vortex on the left is on the lower surface of the horn (i.e. facing towards the neck). The latter vortex is highly unsteady, as the three frames in the figure show. The source of the unsteadiness is buffeting from the unsteady flow off the sloped neck, and the separated flow off the apex off the neck. The vortex on the upper surface, on the other hand, remains steady. Such vortices generate considerable suction forces on the solid surfaces to which they are adjacent (similar vortices are seen to form over delta wings). Hence, if the vortex has an unsteady nature then the forces that are generated are also unsteady.

As the angle of inclination of the model centre-line to the flow increases the vortices become larger, until they burst just after formation, leaving a large wake similar to the side on flow.

4. DISCUSSION

4.1. Wind into Mouth of Horn

The results from the tests with the mouth of the horn pointing into the wind indicate that there are two particularly well defined modes of vortical flow in the mouth which are of concern for angles of incidence below 40°. The first of these, where the flow enters the top and leaves from the bottom of the mouth (Figure 3.2), produces a vortex formation which is probably less intense than that for the second mode. However, the fairly well defined periodicity to the shedding of this vortex from the bottom lip is a worrying feature which would most likely result in periodic forcing along the horn axis. This would produce a tendency for an oscillatory bending action which would be transmitted through the neck to the stem, and down to the base of the structure.

The second mode, where the flow enters the bottom and leaves from the top of the mouth (Figure 3.4), would result in higher unsteady forces along the horn axis due to the greater vortex strength. It appears, however, that these forces are transient rather than periodic in nature and could therefore result in large impulsive forces as the vortex is shed intermittently. A particularly serious situation could arise if this shedding process were to become periodic by "locking on" to some initial oscillation along the horn axis.

As the angle of incidence increases beyond 70° the profile of the horn acts like a bluff body. The wake consists of highly disorganised eddies (Figure 3.6) which would generate random unsteadiness in the along-wind forces. The principal concern is the breadth of this wake, which is many times larger than the stem wake, hence the forces generated would be significantly greater. The location of the horn maximises the bending loads transmitted to the stem and base of the structure. In addition, there is a strong possibility of unsteady torsional loads being transmitted to the stem for this configuration because the horn mouth presents the largest obstruction and is at the maximum offset.

4.2. Wind into Apex of Neck

The results from the tests with the apex of the neck pointing into the wind indicate that there are two main coherent flow structures likely to produce strong unsteady forces. The first of these is the strong periodic shedding of alternate vortices from the neck which is evident at a wind incidence of 0° onto the neck (Figure 3.7). This vortex system would produce both cross-wind and along-wind periodic forces, resulting in bending actions on the structure and to a lesser extent torsional loads due to the neck offset from the stem. In addition the vortices buffet the horn on the stem side, and this may possibly generate transverse force components with the associated bending and torsional actions. The above vortex system is significantly suppressed as the angle of wind incidence increases to about 10° relative to the apex of the neck (Figure 3.8) due to the presence of channelled flow in the gap between stem and horn. This is a beneficial effect and would reduce the level of unsteadiness in the forces mentioned above.

As the angle of wind incidence increases beyond 10° the second coherent flow structure appears, consisting of a pair of conical vortices similar to those shed from a delta wing (Figure 3.9). These vortices have a tendency to produce large transverse forces, which in this case means bending action and torsion about the vertical stem axis. Additionally, the vortex on the stem side is highly unsteady due to the interaction with the neck vortex system, hence the above actions would have a strongly time dependent nature.

4.3. Scalability of Tests

The wind tunnel setup and particular geometric scaling employed for the series of tests reported herein do not facilitate either Reynolds of Froude number scaling. This means that it is not possible to associate the phenomena discussed above with a particular full scale wind speed. Specifically, the Reynolds number dependence of separation lines from smooth surfaces is well appreciated by fluid dynamicists. However, it is the opinion of the authors that, although the details of the experimentally produced vortical structures may well be modified in the full scale case, the basic phenomena will persist at all relevant wind speeds. The tests therefore are considered to provide a comprehensive assessment of the types of unsteady aerodynamic forcing to be expected on the full scale structure.

4.4. Alleviation of Adverse Aerodynamic Characteristics

A range of measures are available which may alleviate the adverse aerodynamic phenomena identified in the wind-tunnel experiments. Suppression of vortex shedding by means of helical strakes is a standard technique. This approach may also be effective as a means of disrupting the conical vortex system found on the Horn surface. Perforation and blockage may provide a means of minimising the effects of recirculation, and hence vortex formation, in the mouth of the Horn.

5. CONCLUSIONS AND RECOMMENDATIONS

Scale model wind-tunnel tests on the Horn have established the existence of adverse unsteady aerodynamic phenomena highly dependent on wind direction. The phenomena comprise a dominant transient vortex system emanating from the mouth of the Horn, periodic vortex shedding from the neck, conical vortices generated on the Horn surface, and effects associated with a general bluff body wake in the lee of the Horn. This aerodynamic behaviour is additional to the known vortex shedding from the support mast.

The qualitative nature of the aerodynamic response is likely to persist in the full-scale structure over a range of flow conditions compatible with the expected wind environment. Consequently, the potential exists for both transient (impulsive) and periodic structural excitation of the Horn originating from aerodynamic sources. However, the limited scope of the present study precludes any quantitative assessment of the magnitude of the imposed aerodynamic loads or of the structural response. Nevertheless, large amplitude structural response can be expected if any of the vortex shedding frequencies are close to the principal natural frequencies of the structure given the expected low damping characteristics of the structure.

Aerodynamic means of alleviating adverse response characteristics are possible; these include perforation, selective blockage and devices such as helical strakes and vortex generators. A detailed assessment of the potential benefits of such measures requires further wind-tunnel investigation, preferably at higher Reynolds numbers.

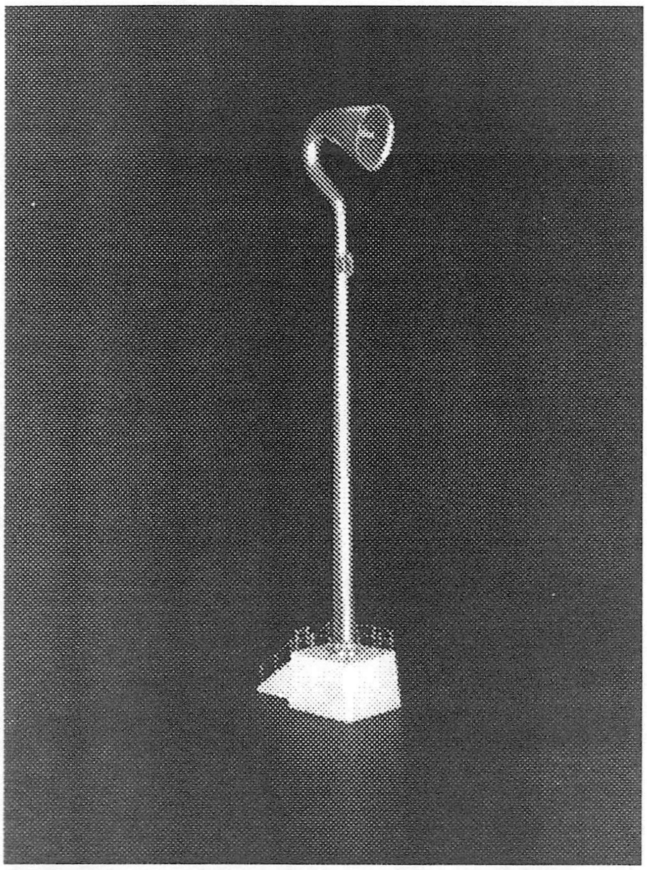


Figure 1.1 Architect's model of the complete Horn

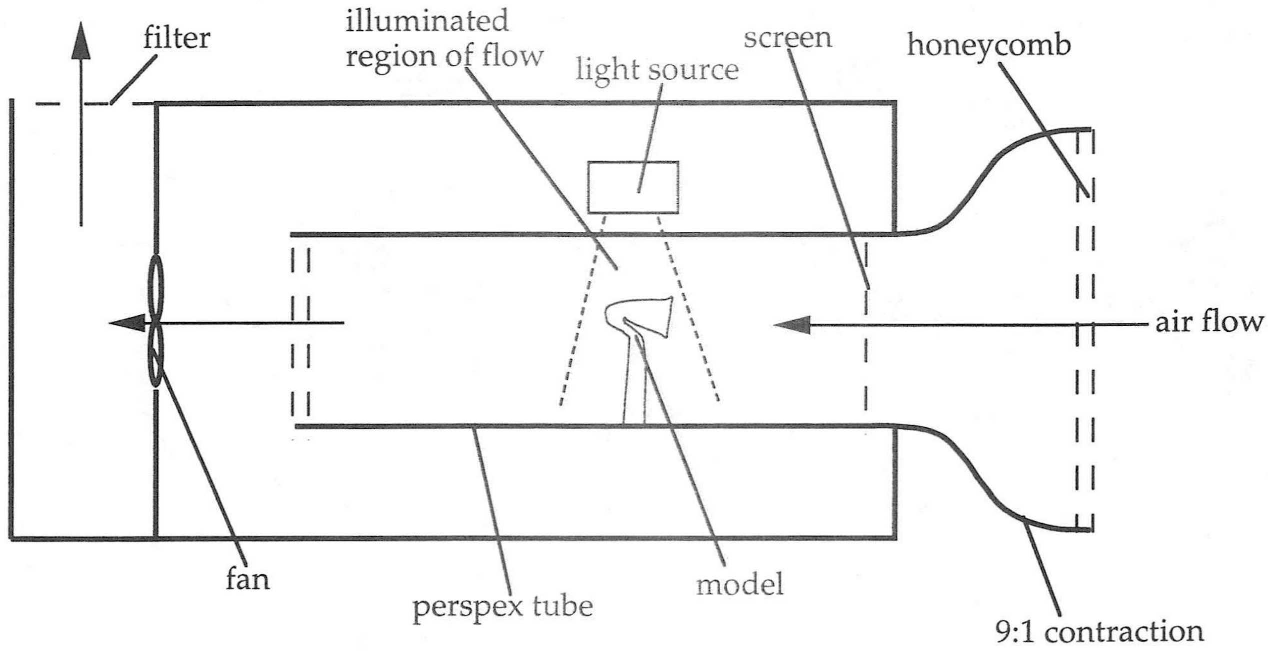


Figure 2.1 Schematic of flow visualisation wind tunnel

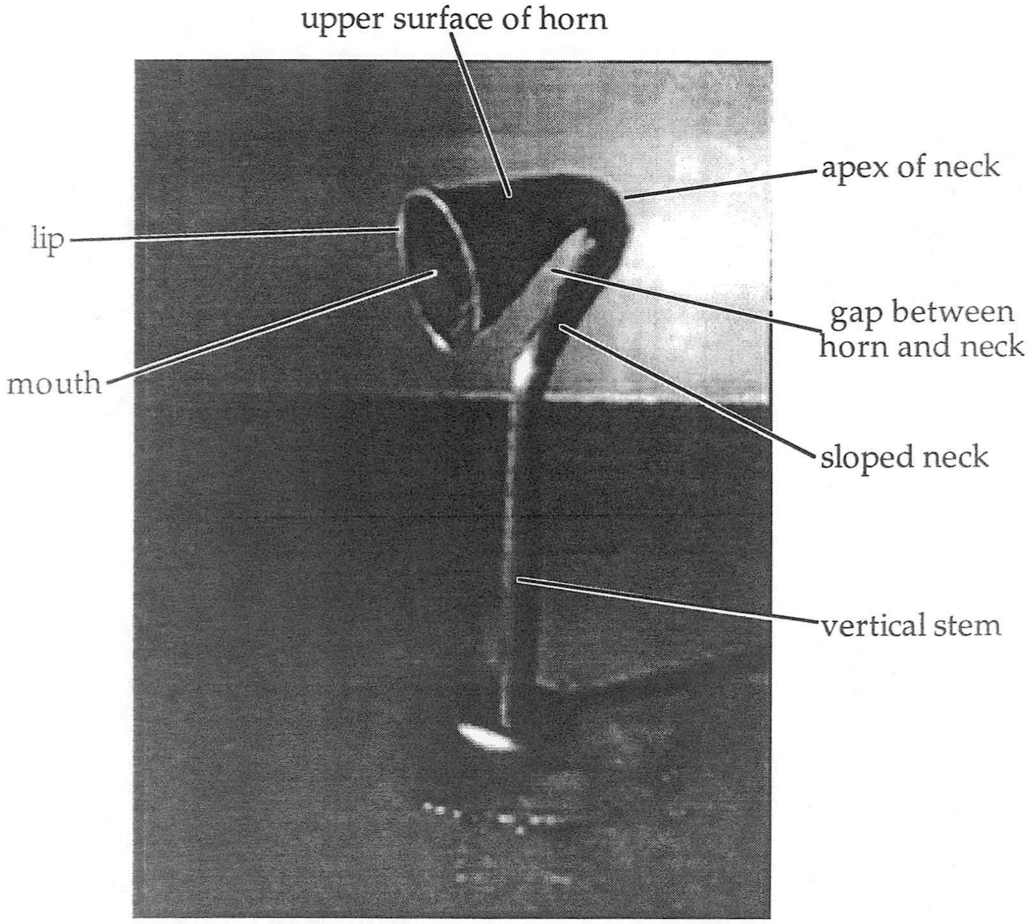


Figure 2.2 The Horn model in the wind tunnel. The terms used in the text are indicated.

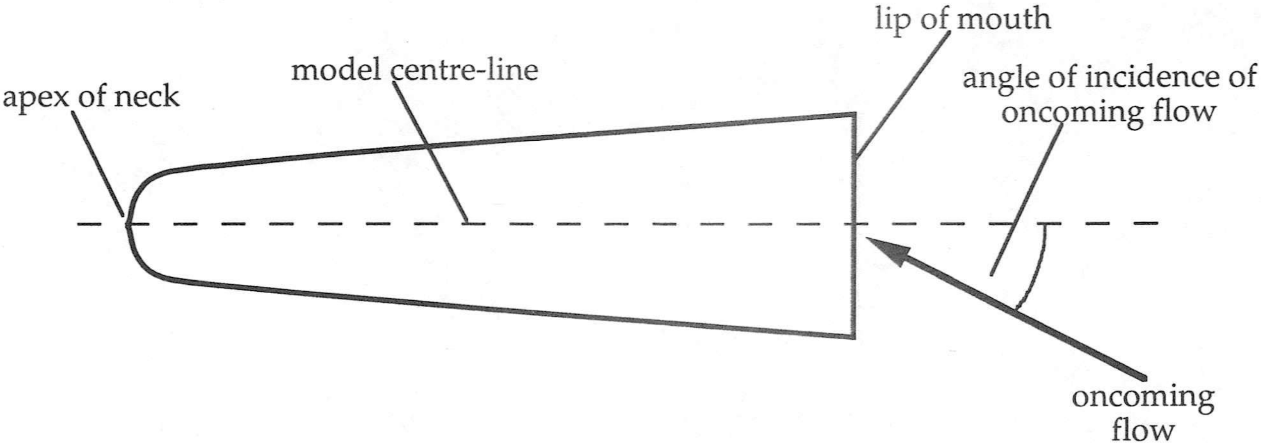


Figure 3.1 Schematic diagram of sense of oncoming flow. View of the Horn from above.

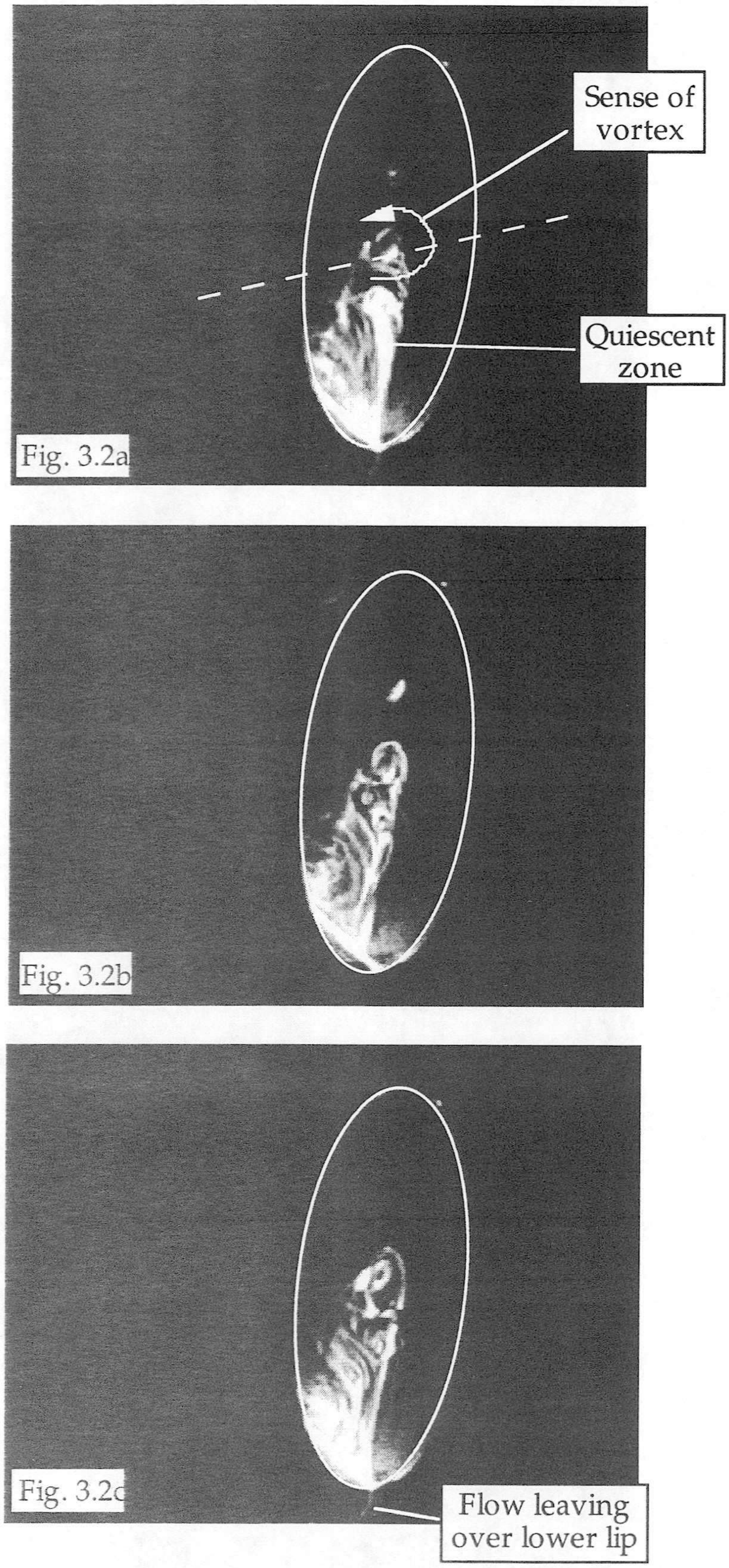


Figure 3.2 First mode of flow observed inside mouth. Model centre-line at 20° to the oncoming flow. The oncoming flow is from the right, and the opening of the mouth is indicated. Air tends to enter through the upper portion of the mouth and leave through the lower portion. The pictures are separated by 4/25 seconds.

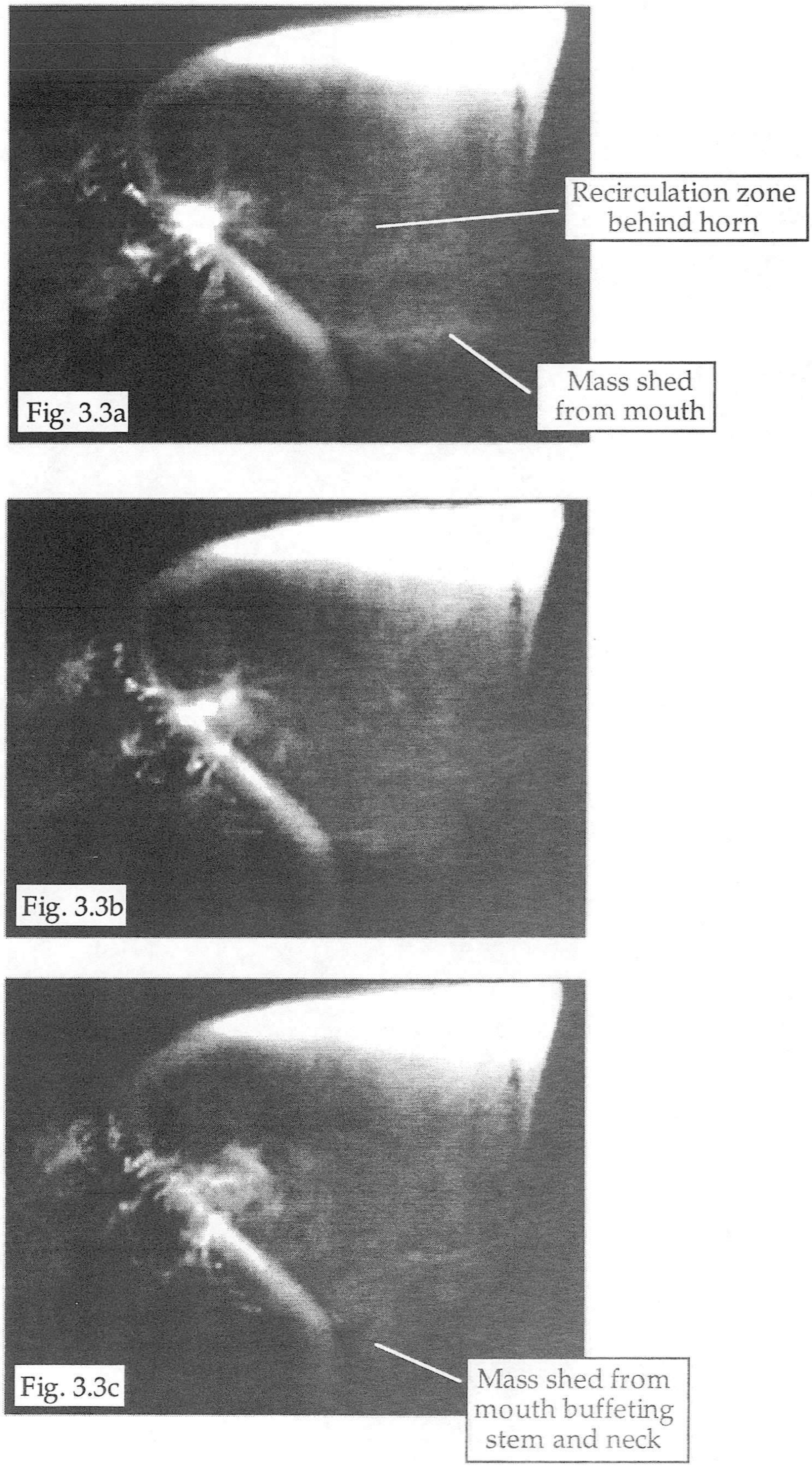


Figure 3.3 Sequence of pictures showing effect of mass shed from lower portion of mouth. The mouth is pointing directly into the wind, and the flow direction is from right to left. The mass just shed from the mouth in fig. 3.3a is about to hit the stem in figure 3.3c. Each frame is separated by 1/25s.

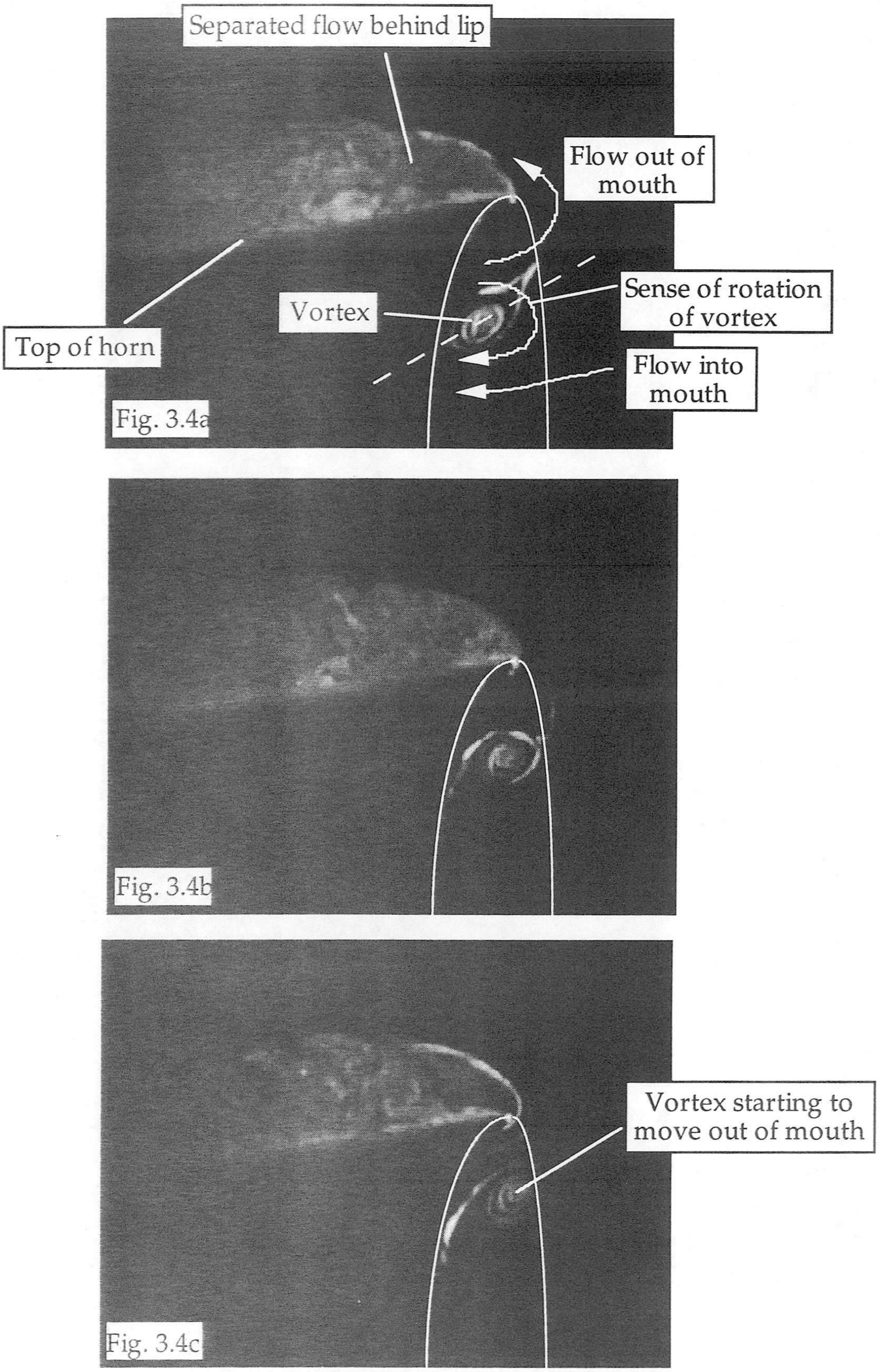


Figure 3.4 Second recirculation mode observed with flow entering mouth. Model centrel-line at 0^{0} to the oncoming flow. Oncoming flow direction from right to left. View is into the top half of the mouth. Laser illumination. Fig 3.4b is 4/25s after 3.4a, and fig 3.4c is 2/25s after 3.4b.

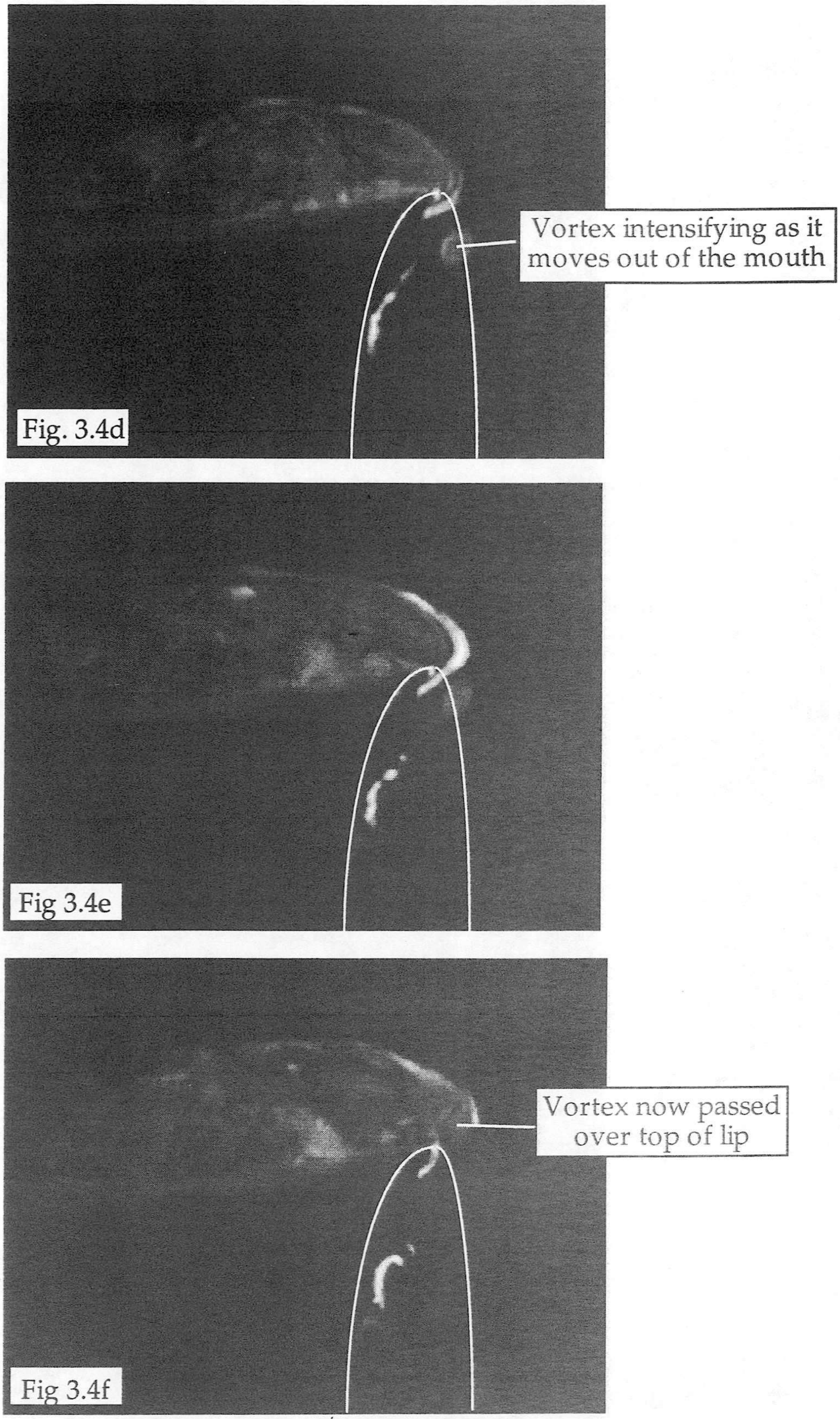


Figure 3.4 (continued) Vortex passing over top lip. Fig. 3.4d is 2/25s after fig. 3.4c. The remaining figures are separated by 1/25 s.

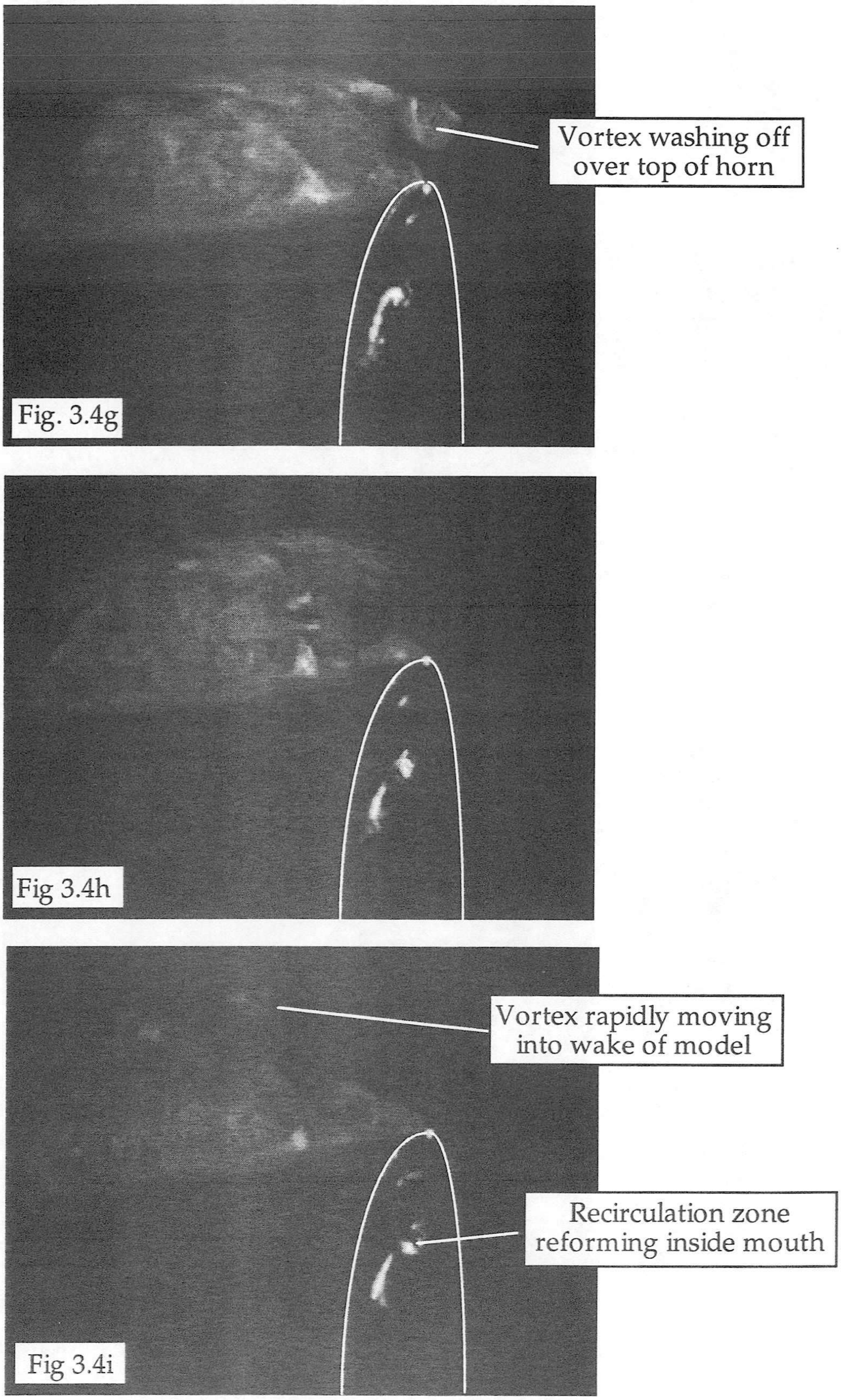


Figure 3.4 (continued) Vortex convecting into wake of model. Frames separated by 1/25s. The beginning of the recirculation zone inside the mouth can also be seen .

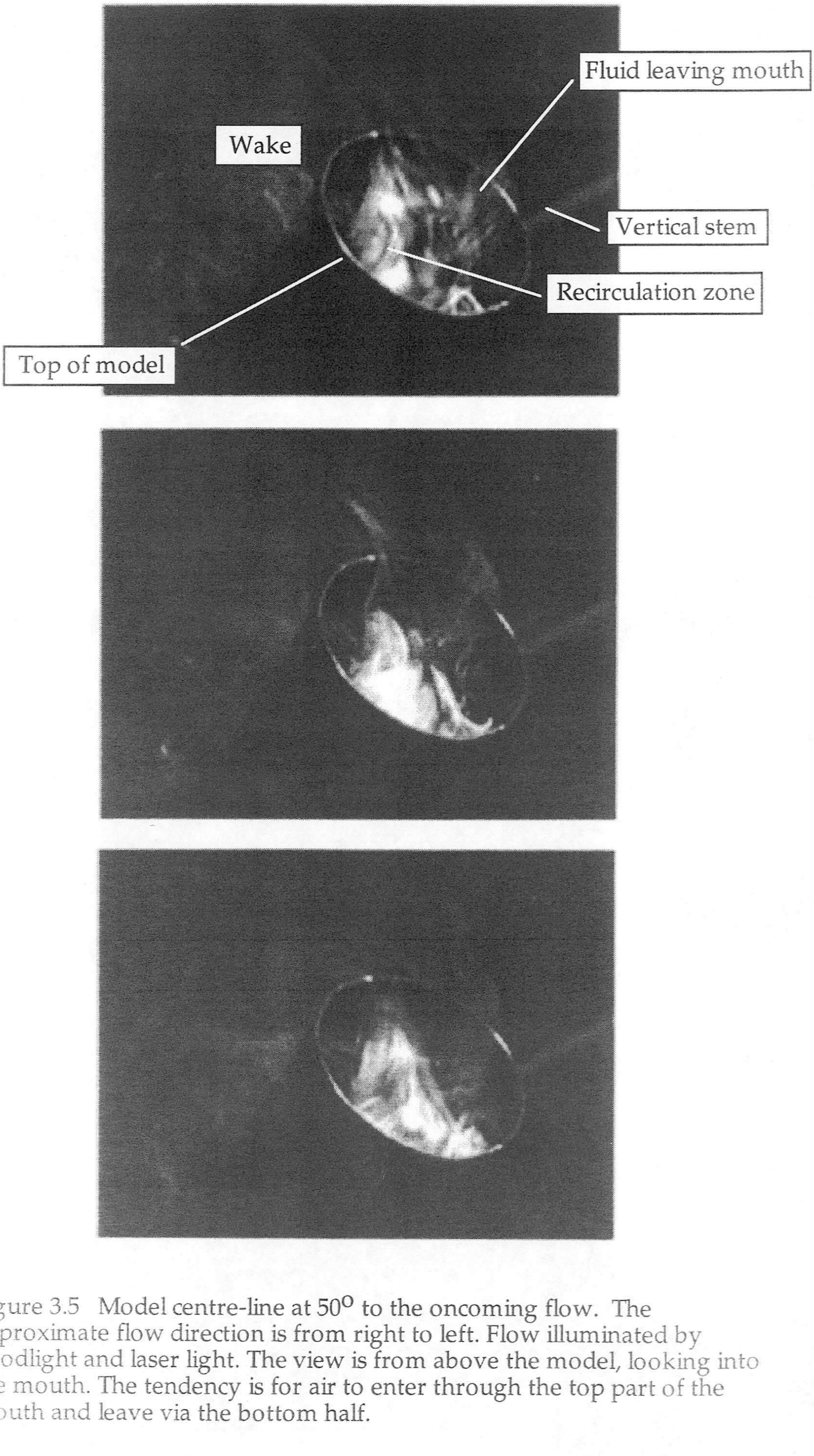


Figure 3.5 Model centre-line at 50^{o} to the oncoming flow. The approximate flow direction is from right to left. Flow illuminated by floodlight and laser light. The view is from above the model, looking into the mouth. The tendency is for air to enter through the top part of the mouth and leave via the bottom half.

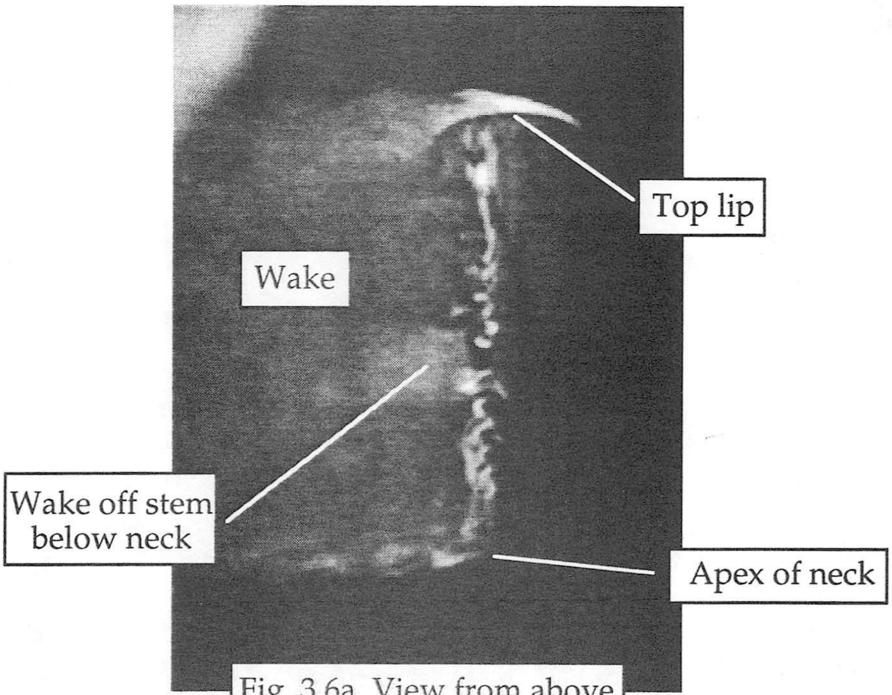


Fig. 3.6a View from above

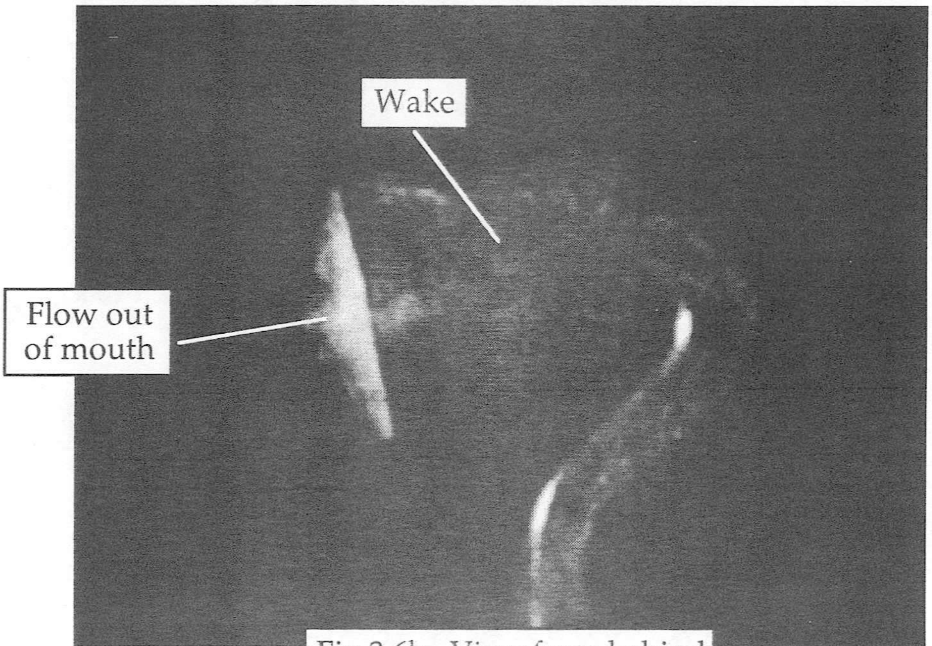


Fig 3.6b View from behind

Figure 3.6 Views of the wake with the model centre-line at 90° to the oncoming flow. In figure 3.6a the flow direction is from right to left, and in figure 3.6b the flow direction is out of the page. Note the large size of the wake in both views.

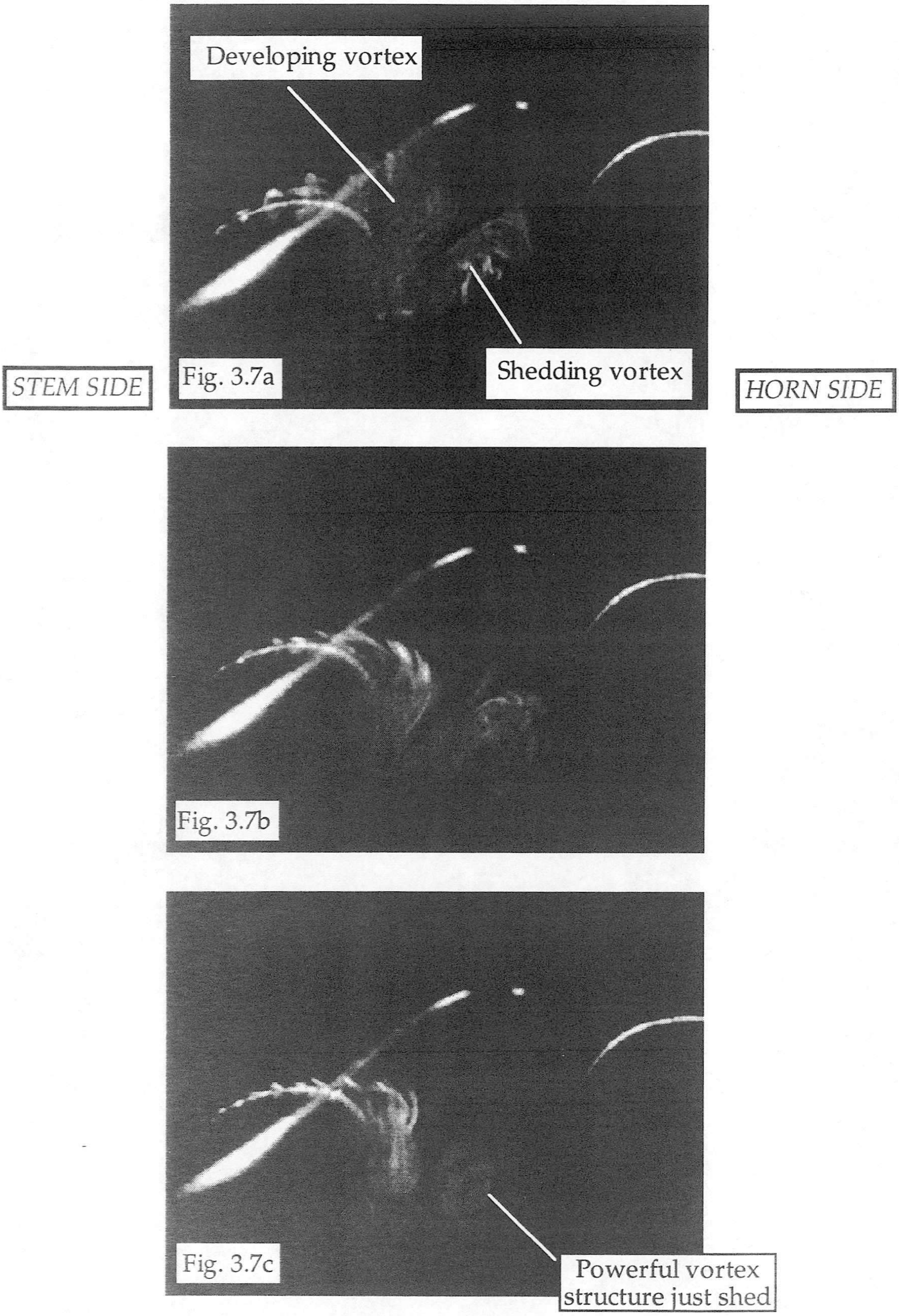
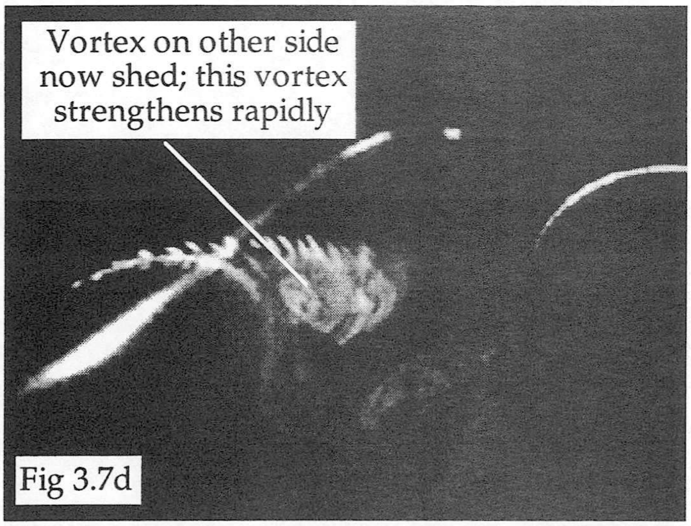


Figure 3.7 Vortex shedding off sloped neck. Apex of neck pointing directly into wind (model centre-line at 180^{o} to the oncoming flow) The flow direction is out of the page and the view is of the flow at the sloped neck/ stem junction from behind. Laser sheet illumination. Each picture is separated by 1/25s.



STEM SIDE

Fig 3.7d

HORN SIDE

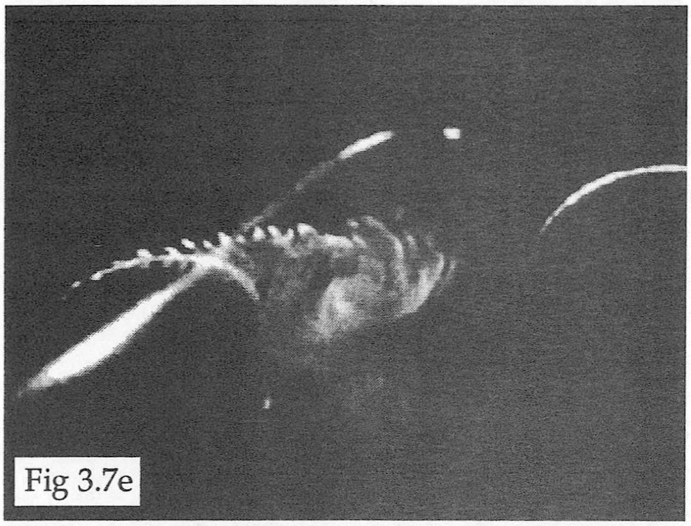


Fig 3.7e

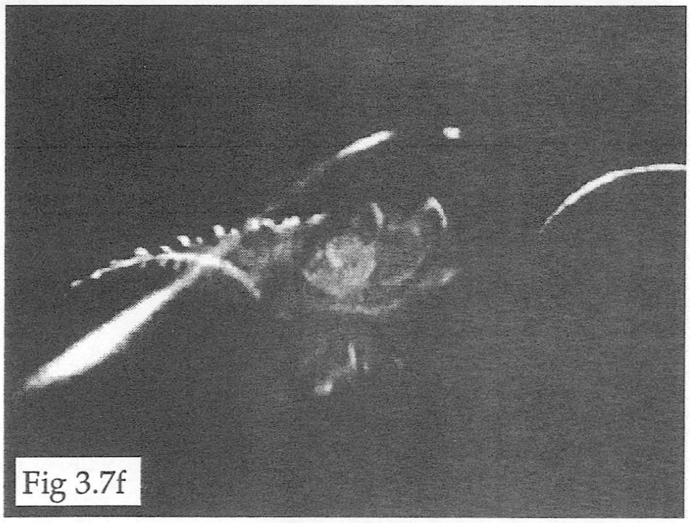


Fig 3.7f

Figure 3.7 Continued

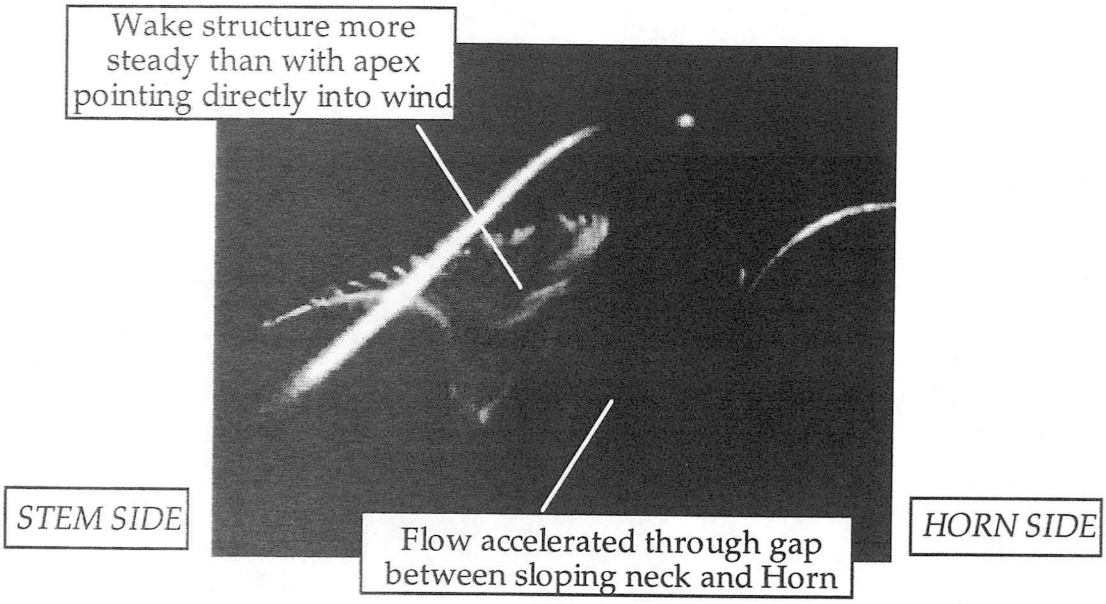


Figure 3.8 Vortex shedding from sloped neck with model centre-line at 170° to the oncoming flow. The flow direction is out of the page, and the view of the flow is from behind.

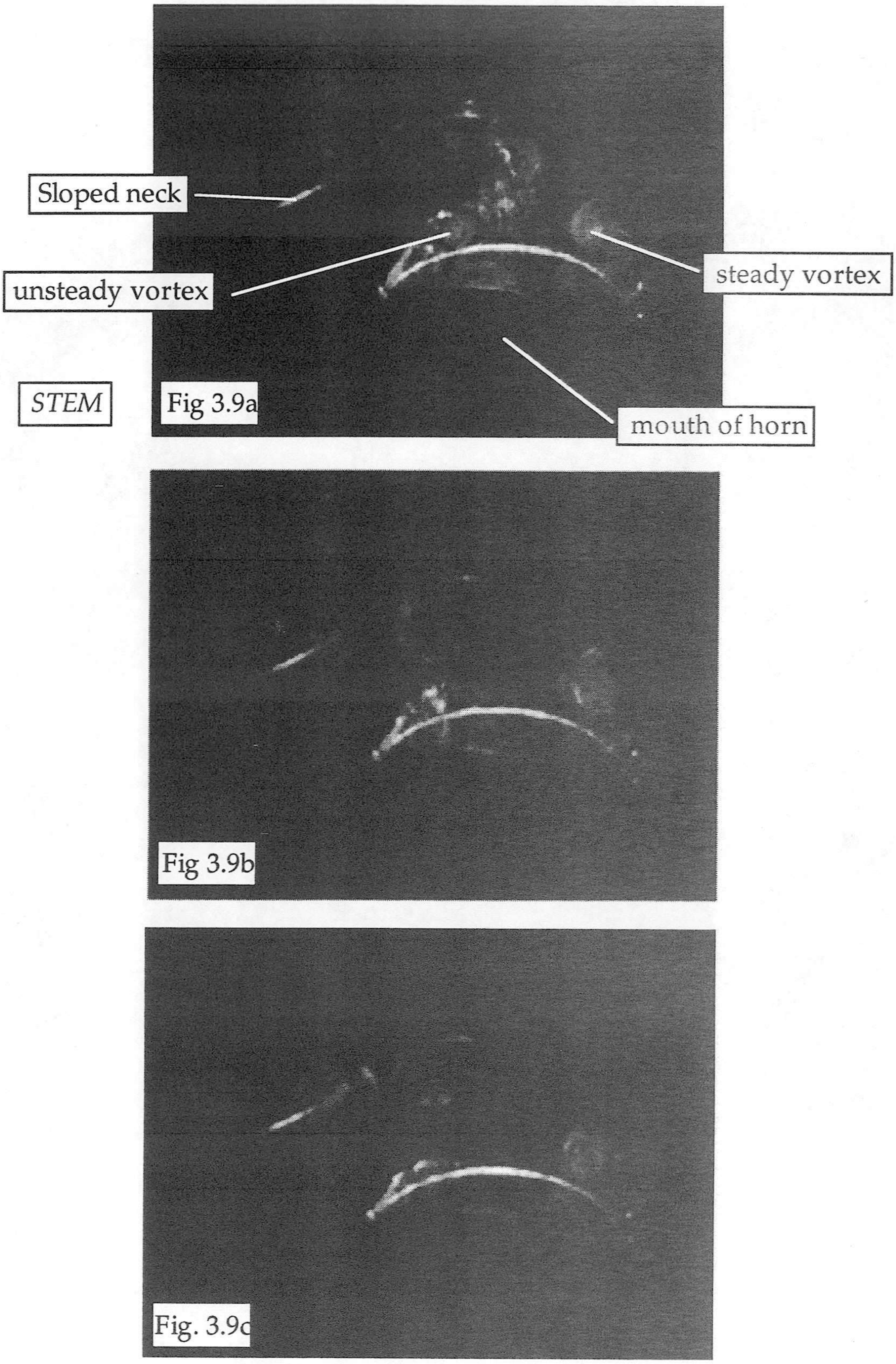


Figure 3.9 Model centre-line at 150° to the oncoming flow. Laser sheet illumination, view of flow over lee side of horn from behind showing flow over horn and sloped neck. The vortices are indicated; the unsteady vortex is over the stem side of the horn. Each picture is separated by 1/25s.