Active Control of Asymmetric Vortex Effects in a Circular Cylinder

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The low speed wind tunnel investigations for the anomalous side force acting on a slender body at high angles of attack are conducted at Reynolds numbers $1.1\times10^5-4.8\times10^5$. The effects of the geometric configurations of the model and the freestream Reynolds number are studied by measuring the aerodynamic force. The anomalous side force that appears on the simple circular cylinder is reduced by the attachment of a cone on the side end of the cylinder, although attachment of another cone on the other side increases the anomalous side force up to the level of the simple cylinder. The anomalous side force can be alleviated by the use of the antennas around the cylinder. The antennas behave as surface roughness and promote the early transition of the boundary layer to the turbulent one.

Nomenclature

C_t	$=(C_x{}^2+C_y{}^2)^{1/2}$
C_x	$=F_x/qS$
C_y	$=F_y/qS$
C_1,C_2	= model cone height
D	= model base diameter
d_a	= diameter of antenna
F_x	= aerodynamic force along the direction parallel to the freestream velocity
F_y	= aerodynamic force along the direction perpendicular to the free stream velocity
h	= space between the antennas and the cylinder
L	= model cylinder length
q	= dynamic pressure $[(1/2)\rho V^2]$
R_c	= critical Reynolds number
R_e	= freestream Reynolds number referred to model base diameter
r_f	= fineness ratio L/D
S	= model base area $[\pi(D/2)^2]$
V	= freestream velocity
ρ	= density
θ_f	$=\tan^{-1}(C_y/C_x)$
θ_0	= 45 deg
δ	= parameter for relative configuration of antennas against the freestream direction

Introduction

VARIOUS kinds of scientific experiments are conducted by using a sounding rocket. Among these, there are many experiments in which payload recovery is necessary (e.g., a material processing experiment). For recovery of the payload, the payload is contained within the separated rocket nose-cylinder, which falls with an aerodynamic deceleration. The separated nose-cylinder is considered as a slender body with a blunted/sharp nose cone and a cylinder; therefore, effective braking is attained by ballistic falling at high angle of attack toward the flight direction.

It is well known that the asymmetric side force acts on the two dimensional cylinder at an angle of attack of 90 deg. Since the geometric configuration is symmetric, the action of the asymmetric side force is anomalous in a sense. This anomalous side force appears at the critical Reynolds number R_c (about 3.4×10^5). Hence, if this anomalous side force acts on the body being recovered at the decelerating phase (i.e., at a high angle of attack to the flight path), the body begins to rotate in the plane perpendicular to the flight direction. This motion is often called "flat spin." A large rate of flat spin seems to be undesirable due to mechanical damage to the payload caused by severe centrifugal forces.

Many studies concerning the various cross flow around slender bodies at high angle of attack have been performed since Allen and Perkins[1] presented the semi-empirical correlation for normal force coefficient. Chapman and Keener,[2] Lamont and Hunt,[3] Clarkson et al.,[4] Kubota et al.[5], and many other authors have studied the side force acting on various types of slender bodies. The review papers by Ericsson and Reding[6,7] suggest that the high level of asymmetric side force depends strongly on the freestream Reynolds number and the angle of attack.

Kamiya et al.[8] and Bearman[9] showed that such an asymmetric side force is due to the asymmetric lock-on of short bubbles on the cylinder surface. Hence, this phenomenon is closely related to the asymmetric vortex generation.

Although the body being recovered is comprised mostly of a circular cylinder, it also has some modifications. For example, it has nose cones on both sides of the cylinder. Also, the body has antennas for a real-time transmission of scientific data. Kubota[5] showed that a cone attached on the cylinder reduces the anomalous side force. The purpose of the present paper is to examine systematically the effect of such modifications on the anomalous side force by measuring the aerodynamic forces acting on such a body.

Wind Tunnel Experiment and Models

The 2-m Göttingen-type low-speed wind tunnel at the Institute of Space and Astronautical Science was used. The freestream velocity was approximately 8-30 m/s. Two types of models were used: a blunted cone-cylinder (model A) and the corresponding cylinder with antennas (model B) as sketched in Fig. 1. The model dimensions and parameters are tabulated in Tables 1 and 2. They are made of polyvinylchloride (PVC). The antennas are made of brass and are supported at one side of the cylinder surface (Fig. 1). Their diameter d_a normalized by the cylinder diameter was 0.024. The space h from the cylinder surface is adjustable. The freestream Reynolds number referred to the base diameter D is $(1.1-4.8)\times10^5$,

Presented as Paper 84-2101 at the AIAA Atmospheric Flight Mechanics Conference, Seattle, WA, Aug. 20-22, 1984; submitted Jan. 8, 1985; revision submitted May 23, 1985.

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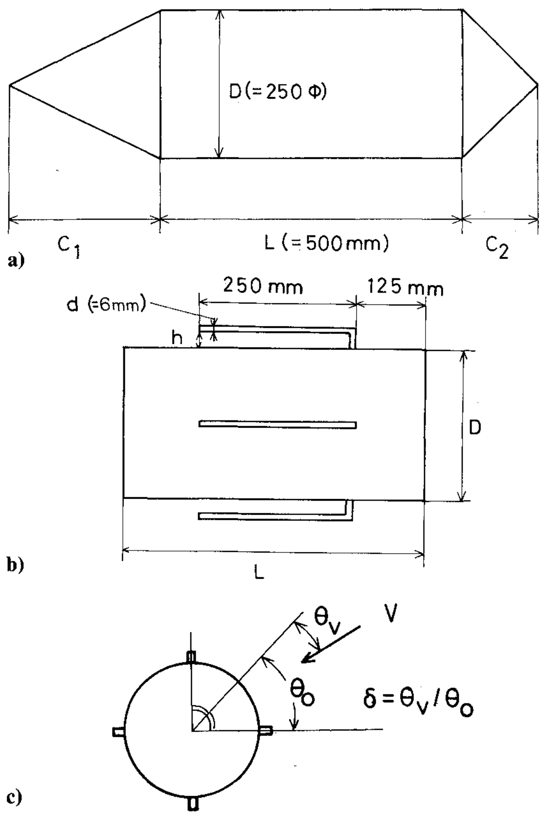

Fig. 1 Schematic figure for models: a) model A, b) model B, and c) definition of δ.

Table 1 Model A dimensions and parameters

Model	C_1	C_2
S00	0	0
S10	$D/2$	0
S20	D	0
S30	$3D/2$	0
S31	$3D/2$	$D/2$
S32	$3D/2$	D
S33	$3D/2$	$3D/2$

Table 2 Model B dimensions and parameters

Model	No. of antennas	h, cm	δ
A4-1(1)	4	1	1
A4-1(7/9)	4	1	7/9
A4-1(6/9)	4	4	6/9
A4-1(3/9)	4	1	3/9
A4-1(0)	4	1	0
A8-0(0)	8	0	1
A8-1(1)	8	1	1
A8-1(0)	8	1	0
A8-3(1)	8	3	1

which covers the critical Reynolds number for the circular cylinder.

The measurement of aerodynamic force was done by using a force balance of the sting type. The overall supporting device is located leeward so as not to disturb the flow (Fig. 2). Flow visualization was also done with the use of oil flow technique.

Experimental Results on Flow Characteristics

Since the anomalous side force becomes maximum at angle of attack of about 90 deg as Kubota[5] showed, the angle of attack at 90 deg is fixed in the following experiments.

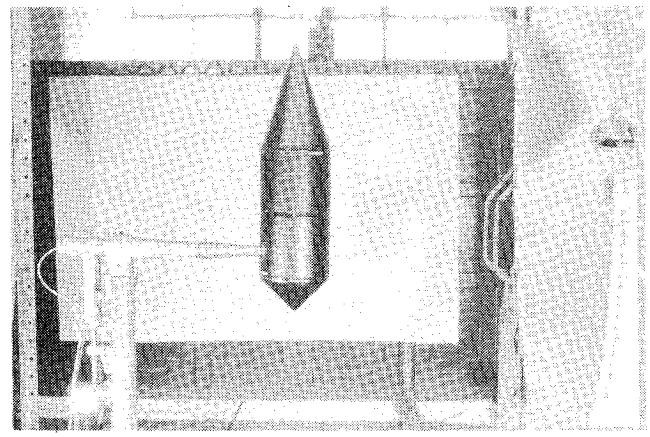

Fig. 2 Model and supporting system.

Effect of Cones

The body being recovered usually has a nose cone (a circular cylinder) attached on one side of the main body. In some cases, the body also has another cone on the other side of the main body, although these are not always of the same size. Kubota[5] showed that a single cone attached on the circular body reduces the anomalous side force, because of three-dimensionality of the flow caused by the cone. Here, the effect of the cone, including the case having two cones one on either side of the cylinder, is investigated systematically.

The side force on the simple circular cylinder (model S00) is shown in Fig. 3. The anomalous side force appears about at the critical Reynolds number R_c. This is caused by the asymmetric attachment of the short bubble on the cylinder surface (or is the result of asymmetric vortex generation). Because of the small fineness ratio (i.e., $r_f = 2$), the side force curve is rather blunt, in comparison with the one for the two dimensional circular cylinder.[5] The total aerodynamic force shows smooth transition to a smaller value, around $R_e \simeq 2.5 \times 10^5 - 3.8 \times 10^5$ (Fig. 4). This shows that the boundary layer undergoes a change from laminar to turbulent. This transition can be seen in all cases, including the case with cones; therefore, the cones on the cylinder do not have any affect on the transition process.

Since the total aerodynamic force is different from case to case, it is convenient to observe a deviation angle of the aerodynamic force $\theta_f = \tan^{-1}(C_y/C_x)$ to compare the contribution of the anomalous side force, instead of observing C_y directly. In fact, the angle θ_f can be closely related to the flat spin rate.[10] As can be seen from Fig. 5, the side force decreases when the cone with decreasing cone angle is attached on the side of the cylinder (the other side remains flat). This is caused by the fact that the cone increases the three dimensionality of the flow.[5] However, when another cone with decreasing cone angle is attached on the other side of the cone cylinder, the force deviation angle θ_f increases again and recovers up to a value comparable to the one for the simple cylinder. This is due to the fact that the flow recovers the two-dimensionality (at the central part of the cylinder), which would be lost in the case of the single cone-cylinder.

Cylinder with Antennas

For practical applications, it is useful to find a device to alleviate the abovementioned side force which causes the flat spin motions. Since the flat spin motion is originated by the lock-on of the short bubble on the cylinder (or as a result of the generation of asymmetric vortex), an effective way to alleviate this side force for the boundary layer appears to be in early transition to turbulence. This may be attained by the use of surface roughness.[11] For this purpose, the study of the side force alleviation technique by a tripping wire was performed by Rao[12] and Kubota.[5]

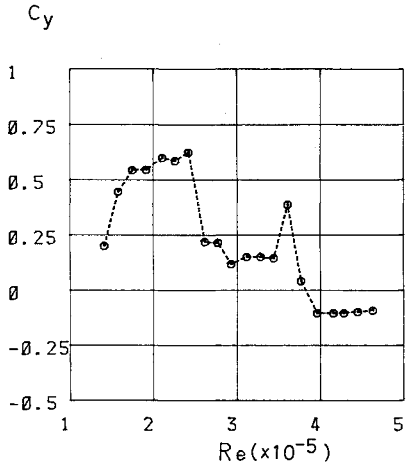

Fig. 3 Side force vs Reynolds number in model S00 (simple cylinder).

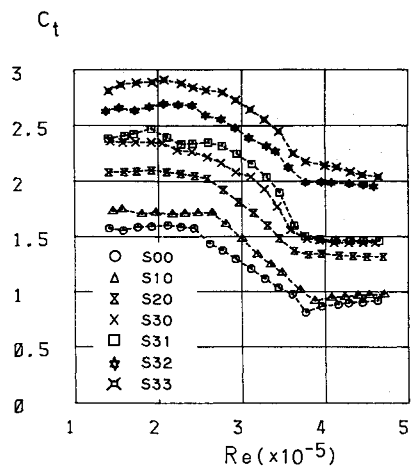

Fig. 4 Total aerodynamic force C_t vs Reynolds number.

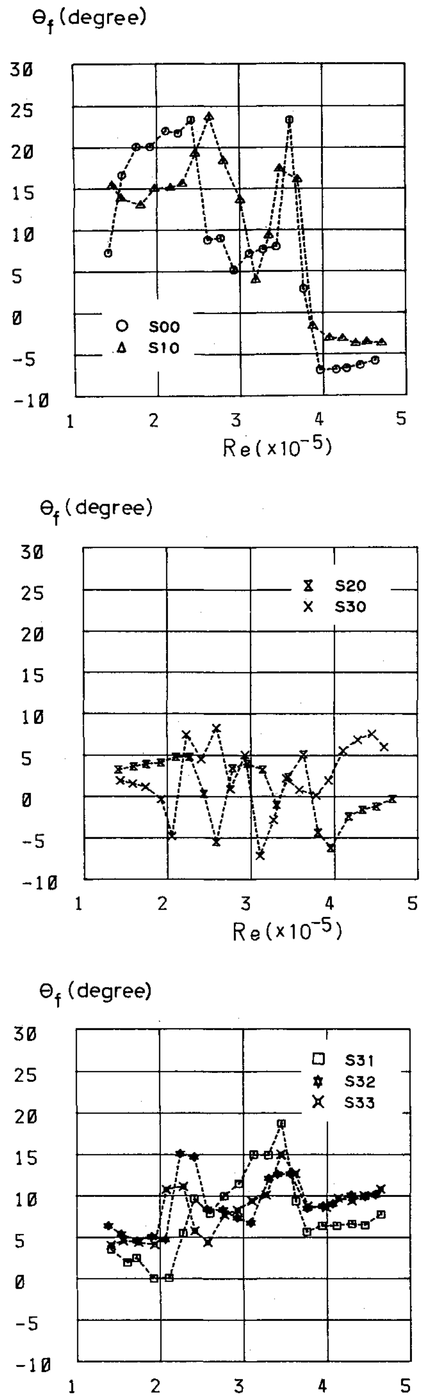

Fig. 5 Deviation angle θ_f vs Reynolds number.

The body being recovered commonly has some antennas that are employed for a real-time transmission of scientific data. These antennas are attached on the cylinder surface parallel to the cylinder axis, although these are not attached close to the surface. Hence, it would be convenient if these antennas can be used to alleviate the anomalous side force. In reality, it can be expected that these antennas will work on the cylinder surface as surface roughness and alleviate the anomalous side force, although there is some space between these antennas and the cylinder surface.

In the present investigation, the effect of the antennas on the circular cylinder is examined systematically. In our model, the antennas are arranged at equal intervals circumferentially. The free parameters about the antenna arrangement are 1) the space between the antennas and the cylinder surface, 2) the number of antennas, and 3) the relative configuration of the antennas against the freestream direction.

Effect of the Space Between Antennas and Cylinder Surface

Figure 6 shows the side force acting on a cylinder having eight antennas with varying amounts of space from the cylinder surface, from $h = 0$ to $h = 3$ cm. As expected, the side force vanishes completely, $h = 0$, when the antennas are attached close to cylinder surface. In this case, the antennas act as tripping wires, although they are short and are not stretched over the cylinder length. When the space $h = 1$ cm, the side force appears, although it is sufficiently small in comparison with that of the simple cylinder. Furthermore, when $h = 3$ cm, the side force appears to be the same order as that of the simple cylinder. Hence, it can be said that the larger the space becomes, the weaker the effects of the antennas on the surface; therefore, the less the antennas act as a surface roughness. However, our experimental results show that even when the antennas are separated from the cylinder surface by an appropriate distance (i.e., $h = 1$ cm) for a real antenna arrangement, they can be active as surface roughness and can alleviate the anomalous side force sufficiently.

When the antennas are attached to the cylinder, the total aerodynamic force C_t shows an early transition to turbulence, in comparison with the case of the simple cylinder (Fig. 7). The surface flow pattern of cylinder with and without the antennas shows this more clearly (Figs. 8a and 8b, respectively). In this figure, the flow separation is indicated by the

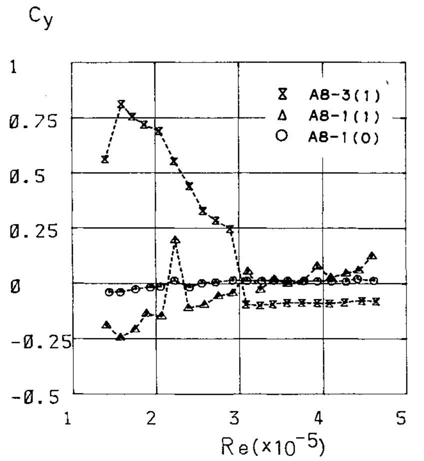

Fig. 6 Side force vs Reynolds number for the cylinder with eight antennas.

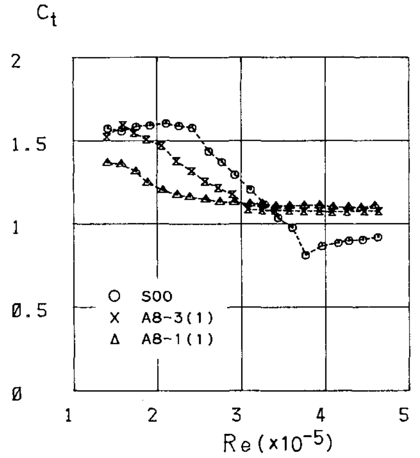

Fig. 7 Total aerodynamic forces vs Reynolds number.

white oil collection lines. In comparison with the simple cylinder (the separation angle is approximately 80 deg), the separation line behind the antennas is drawn back (the separation angle is approximately 110 deg.). This shows that these antennas work as a surface roughness and promote an early transition of the boundary layer, although there is space between the antennas and the cylinder surface. Hence, these antennas can work in a manner similar to a trip wire for alleviation of the anomalous side force.

Effect of Relative Configuration of the Antennas Against Freestream Direction

The effectiveness of the antennas as a surface roughness depends on the relative configuration against the freestream direction, as can be expected from the difference of the geometric configuration of wakes that are generated by the antennas and impinge upon the cylinder surface. In fact, the side force acting on the cylinder with four antennas shows a dependency on the relative configuration of the antennas against the freestream direction (Fig. 9). Although the side force almost completely vanishes at $\delta = 0$, it appears around $\delta = 1$ (lateral meridian) in the same order with that of the simple cylinder. As can be seen from the geometrical configuration, the effect of the antennas as surface roughness is weakest at $\delta = 1$. Hence a greater side force appears at this relative configuration. On the other hand, when $\delta = 0$, the wakes of the antennas in front of the cylinder strike the cylinder surface and act as surface roughness. Hence, in this configuration, the anomalous side force can be alleviated sufficiently. As noted by Ericsson and Reding,[13] the antennas must be ahead of the lateral meridian in order to affect a change in the boundary layer early enough to alter the flow separation type from critical to turbulent.

Effect of the Number of Antennas

In practical use, it is preferable if the side force becomes sufficiently weak in each configuration against the freestream direction. Unfortunately, in the case with four antennas, the anomalous side force appears around $\delta = 1$. On the contrary, in the case with eight antennas, it can be expected that the side force will become sufficiently weak in every δ, since only the

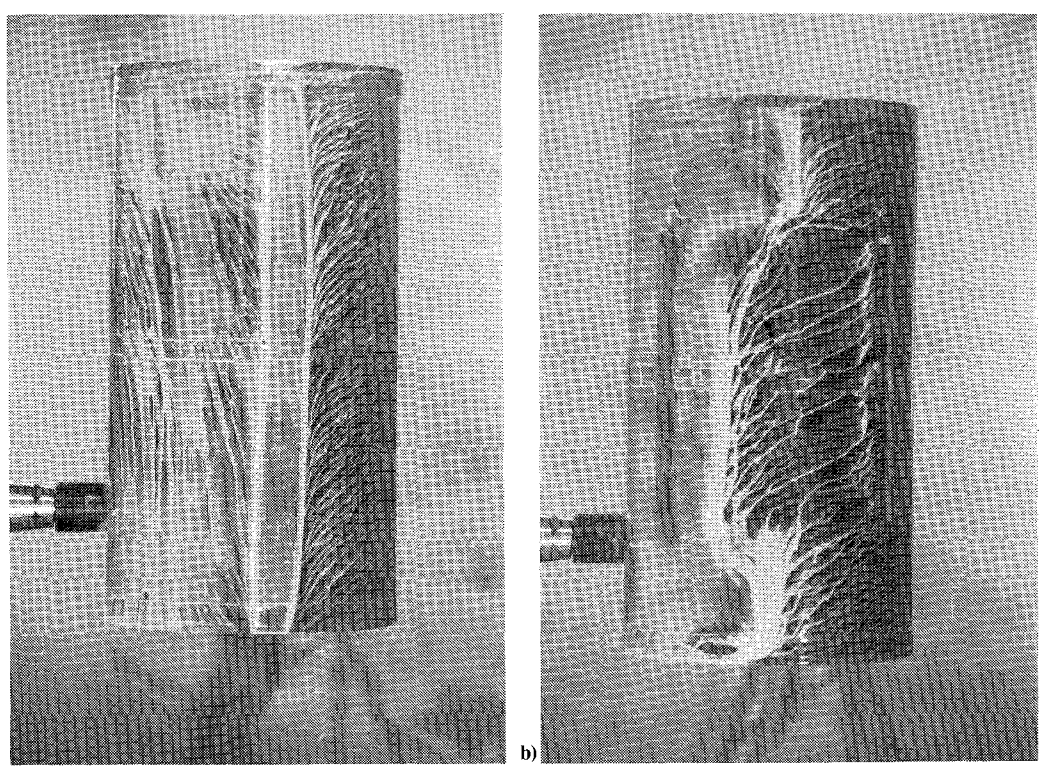

Fig. 8 Surface flow patterns at $Re = 2 \times 10^5$ for a) model S00 and b) model A4-1(0).

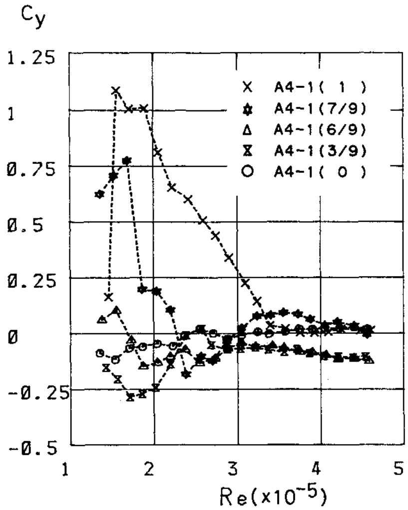

Fig. 9 Side force vs Reynolds number for the cylinder with four antennas.

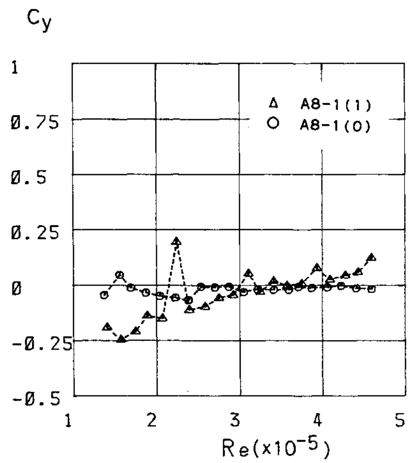

Fig. 10 Side force vs Reynolds number for the cylinder with eight antennas.

weak side force appears on the cylinder even at $\delta = 1$ and the anomalous side force vanishes almost completely at $\delta = 0$ (Fig. 10). Therefore, it can be said that eight antennas attached on the circular cylinder are sufficient for alleviation of the anomalous side force in every direction against the freestream direction.

Conclusion

Low-speed-wind-tunnel investigations for the anomalous side force acting on slender bodies at high angles of attack were conducted in association with the static force measurements and flow-visualization technique. Major conclusions are as follows:

1) A single cone attached on the cylinder reduces the anomalous side force if its cone angle is small enough.

2) Another cone attached on the other side of the cone cylinder causes the anomalous side force of the same order as that of the simple cylinder.

3) The antennas attached on the cylinder surface can alleviate the anomalous side force. Although the alleviation becomes weak depending on the spacing between the cylinder surface and the antennas, sufficient alleviation can be attained even at spacing of $h = 1$ cm.

4) Using antennas to alleviate the side force depends on the relative configuration against the freestream direction. In the cylinder with four antennas, the anomalous side force comparable to that of the simple cylinder appears around $\delta \approx 1$. Eight antennas are sufficient to alleviate the anomalous side force equally in every configuration against the freestream direction.

Acknowledgment

The authors are greatly indebted to Prof. M. Hinada for his valuable suggestions. They also acknowledge Prof. H. Oguchi for valuable discussions.

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