Field observation and numerical analysis of a rotating pipe in flight

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Abstract

The present purpose is to reveal the mechanism of a flying pipe from an aerodynamic point of view. At first, we conduct field observations of a flying pipe using a pair of high-speed video cameras, together with three-dimensional motion analyses. In addition, we conduct numerical analyses by a finite difference method based on the MAC scheme. As a result, the observed orbit is approximated to be not an obvious parabolic curve but rather a straight line, after an initial instable and complicated curve. The stable flight with this approximately-straight orbit suggests the importance of aerodynamics in flying mechanism. More specifically, the model is in an unstable and complicated flight during an initial flight, afterwards becomes in a stable and approximately-straight flight. In the initial instable and complicated flight, the model flies fluctuating its posture upward, downward, left-ward and right-ward. As flight distance increases, the absolute value and the amplitude of moment becomes small to zero. During such a decaying and stabilising process, the gyroscopic effect plays a primary role balancing not angular acceleration of the model but aerodynamic fluid moment. In the stable and approximately-straight flight, the flow in the stable and approximately-straight flight is nearly the velocity-potential one, and accompanies very-small drag force. And, we could ignore the influence of model's rotation upon the flow and the orbit. In this context, the model's rotation is only to stabilise its posture, and gives negligible contribution upon its aerodynamics.

Keywords : Wake, Three dimension, Experiment, Numerical analysis, Pipe, Tube, Rotation

1. Introduction

The present study concerns the aerodynamics of a flying pipe or a flying tube in rotation, with which we might be familiar as “X-zyLo™” (WMC, 2017). Some flying pipes could fly faster than such a similar projectile as a flying disc like “Frisbee®,” and farther than a football. While the flow past a three-dimensional object at high Reynolds numbers has been important at various practical aspects in aeronautical and mechanical engineering fields as well as sport fields, it is one of rather recent topics in the long history of fluid mechanics. As three-dimensional objects, it seems appropriate to regard axisymmetric objects with simple and basic geometries like a sphere and a disc, whose knowledge are required in the analyses of many flying or suspended objects in fluid. However, even the flow past an axisymmetric object has not been revealed enough in comparison with such a two-dimensional object as a circular cylinder, despite of wide ranges of its applicabilities. Among the flows past three-dimensional axisymmetric objects, there have been less researches concerning the flow past a pipe or a tube which is another simple axisymmetric object. And, such researches have been still less active than a sphere or a disc, although they are useful in many industrial fields such as the designs

for combustors, ventilator nacelles, screw casings, streamers and flowmeters as well as flying toys. While there have existed few researches on the flow past a pipe (Hirata et al., 2013), we can find several researches on the flow past a ring, a torus or a washer (Takamoto, 1987; Leweke et al., 1993; Hirata et al, 2001; Sheard et al., 2005; Hirata et al., 2006; Hirata et al., 2007). For renewable-energy applications, the flow has attracted our attention in the context of a new-concept windmill design (Ohya et al, 2006). However, in all the previous researches, a pipe is not in rotation but stationary.

The present purpose is to reveal the mechanism of a flying pipe from an aerodynamic point of view. At first, we conduct field observations of a flying pipe in rotation using a pair of high-speed video cameras, together with three-dimensional motion analyses based on their recorded stereo images, which quantitatively show orbit, and translation speed angular velocity of the flying pipe to specify acting moments and forces. In addition, we conduct numerical analyses by a finite difference method based on the MAC scheme. More specifically, we numerically investigate the flow past a rotating stationary pipe which is immersed parallel to a uniform mainstream, and discuss its aerodynamics.

2. Methods

2.1 Model and Parameters

Figure 1 shows the present model: namely, a rotating pipe flying in stationary fluid. Governing geometric parameters in non-dimensional forms are a reduced diameter d/t and a reduced length l/t , where the model's dimensions d , l and t denote diameter, length (the axial dimension of pipe's cross section) and thickness (the cross-axial dimension of pipe's cross section) of the pipe, respectively. d/t and l/t represent the geometric parameters corresponding to pipe's curvature and length, respectively. Both the geometric parameters are given as follows.

$$\frac{d}{t} = \frac{d_o + d_i}{d_o - d_i} \quad (1)$$

$$\frac{l}{t} = \frac{2l}{d_o - d_i} \quad (2)$$

To be exact, d is the pipe's mean diameter $(= (d_o + d_i)/2)$. d_i is the diameter of pipe's inside. And, d_o is the diameter of pipe's outside.

Governing kinetic parameters in non-dimensional forms are the Reynolds number Re and a rotation parameter Ω^* , where we regard t as a characteristic length scale. Ω^* represents the ratio of pipe's rotating velocity to pipe's translation speed U_∞ . Then, Re is defined by the following equation.

$$Re = \frac{U_\infty t}{\nu} \quad (3)$$

where ν is the kinematic viscosity of fluid. And, Ω^* is defined by the following equation.

$$\Omega^* = \frac{\frac{d}{2}\Omega}{U_\infty} \quad (4)$$

We should note that the model is not in rotation, when $\Omega^* = 0$.

Lift coefficient and C_L drag coefficient C_D are defined by the following equations.

$$C_L = \frac{L}{\frac{1}{2}\rho U_\infty^2 S} \quad (5)$$

and

$$C_D = \frac{D}{\frac{1}{2}\rho U_\infty^2 S} \quad (6)$$

where L and D are lift force and drag, respectively. S is the wing area, which is equal to $2dl$.

2.2 Field Observation

Figure 2 shows a schematic diagram of the present experimental apparatus for field observation. The motion of a model (No. 1 in the figure), which is thrown by a player, is recorded by a pair of high-speed video cameras (No. 2). One camera is fixed to observe model's front view, and the other is fixed to observe model's side view. Two cameras are synchronised with each other by a trigger-pulse generator (No. 3). A personal computers (No. 4) is connected to one camera by IEEE1394 and to the other by a LAN cable, in order to initialise/monitor the cameras and in order to storage/analyse the recorded data. For calibration of the present stereo system, we use a transparent rectangular parallelepiped or four colour corns (No. 5).

Figure 3 shows the photographs of models for field observation: namely, (a) a commercial model and (b) a simplified laboratory model. The former is for reference. The latter is the main model for field observations, and is simply called as 'model' in field observations. Figure (c) indicates the details of the latter. Table 1 summarises the model's dimensions and mass, together with geometric parameters in non-dimensional forms.

In order to calculate forces and moments acting on the model using consecutive series of both the model's position and the model's attitude obtained by three-dimensional motion analysis with a ground-fixed coordinate system (x_E, y_E, z_E) , we introduce the Euler angles. Figure 4 shows the definition of the Euler angles Ψ , θ and Φ for motion analysis. The origin O of coordinates is located at the model's mass centre G, while the origin O_E of (x_E, y_E, z_E) is the place where the model is just released. A coordinate system (X_E, Y_E, Z_E) is comparative to the earth surface. Another (X_1, Y_1, Z_1) is a rotated (X_E, Y_E, Z_E) by Ψ about the Z_E axis. Another (X_2, Y_2, Z_2) is a rotated (X_1, Y_1, Z_1) by θ about the Y_1 axis. The other (X, Y, Z) is a rotated (X_2, Y_2, Z_2) by Φ about the X_2 axis. Thus, the momenta and angular momenta equations of the model in the object-fixed coordinate system (X, Y, Z) are as follows.

$$m(\dot{U} + QW - RV) = -mg \sin \theta + F_X, \quad (7)$$

$$m(\dot{V} + RU - PW) = mg \cos \theta \sin \Phi + F_Y, \quad (8)$$

$$m(\dot{W} + PV - QU) = mg \cos \theta \cos \Phi + F_Z, \quad (9)$$

$$I_{XX}\dot{P} - I_{XZ}\dot{R} + (I_{ZZ} - I_{YY})QR - I_{ZX}PQ = M_X, \quad (10)$$

$$I_{YY}\dot{Q} + (I_{XX} - I_{ZZ})RP + I_{XZ}(P^2 - R^2) = M_Y, \quad (11)$$

and

$$-I_{XZ}\dot{P} + I_{ZZ}\dot{R} + (I_{YY} - I_{XX})PQ + I_{XZ}QR = M_Z. \quad (12)$$

In Eqs. (7) – (9), in g denotes the gravitational acceleration, and U , V and W are translation-speed components of the model. In Eqs. (7) – (12), P ($= \Omega$), Q and R are angular-velocity components of the model. $[I_{ij}]$ with $ij = X, Y$ or Z is the inertia-moment tensor of the model. F_X , F_Y and F_Z are external (fluid) force components. And, M_X , M_Y and M_Z are external (fluid) moment components. An over dot denotes acceleration or angular acceleration. Non-linear terms on the left hand of Eqs. (10) – (12) produce the gyroscopic-moment effect.

2.3 Numerical Analysis

In many actual situations, most of the flow for $Re < 10^6$ could be usually regarded as incompressible and viscous. So, we consider the incompressible full Navier-Stokes equations for the present numerical analyses. We approximately solve the equations using a finite-difference method with the MAC scheme in pressure-velocity coupling, a third-order-upwind difference in spatial discretisation of convective terms, a second-order-central difference in spatial discretisation of the other terms, and the Euler explicit method in time marching.

In computation, we consider a rotating pipe in a uniform mainstream, instead of a rotating flying pipe in stationary fluid. As a spatial grid, we use a staggered cylindrical grid with unequal spacing. Most of the grid numbers in radial, azimuthal and axial directions are 200, 42 and 460, respectively. Computational-domain sizes in radial and axial directions are $103t$ and $274t$, respectively. Table 2 summarises computational conditions. Such computational parameters as grid number and computational domain are determined by many preliminary trials, to achieve negligible

influences upon results.

3. Results and discussion

3.1 Wide-range observation

Figure 5 shows an example of field observations; namely, two instantaneous images obtained by a pair of high-speed video cameras (in figures (a) and (b)), together with the orbit by three-dimensional (3D) motion analysis. Besides, figure (c) shows the analysed orbit in 3D space as the two cameras are synchronised for stereophotography photos. A model flies in the direction of a red arrow in each figure. And, each yellow dot in figures (a) and (b) corresponds to one rotation of the model. We can see that the observed orbit is approximated to be not an obvious parabolic curve but rather a straight line, after an initial instable and complicated curve. The stable flight with this approximately-straight orbit suggests the

Fig. 1 Model: a rotating pipe flying in stationary fluid.

Fig. 2 Experimental apparatus for field observation.

(a) Commercial model (X-zyLo™)

(b) Model (simplified)

(c) Details of (simplified) model

Fig. 3 Experimental model for field observation.

Table 1 Model's dimensions and mass, together with geometric parameters in non-dimensional forms.

	Commercial model (X-zyLo™)	Model (simplified)
Diameter d	0.096 m	0.1 m
Thickness t	0.001 m	0.001 m
Length l	0.061 m (max.), 0.048 m (min.)	0.06 m
Mass m	0.023kg	0.017 kg
Reduced diameter d/t	96	100
Reduced length l/t	61 (max.), 48 (min.)	60

Fig. 4 Euler angles Ψ , θ and ϕ for motion analysis. The origin O of coordinates is located at a models mass centre G. A coordinate system (X_E, Y_E, Z_E) is comparative to the earth surface. Another (X_1, Y_1, Z_1) is a rotated (X_E, Y_E, Z_E) by Ψ about the Z_E axis. Another (X_2, Y_2, Z_2) is a rotated (X_1, Y_1, Z_1) by θ about the Y_1 axis. The other (X, Y, Z) is a rotated (X_2, Y_2, Z_2) by ϕ about the X_2 axis.

Table 2 Computational conditions.

Computational domain	R (in radial direction)	103t
	L (in streamwise direction)	274t
Grid number	N_r (in radial direction)	200
	N_θ (in azimuthal direction)	42
	N_z (in streamwise direction)	460

Fig. 5 An example of field observation; instantaneous images by a pair of high-speed video cameras, and the orbit by three-dimensional motion analysis. A model flies in the direction of an red arrow in each figure.

importance of aerodynamics in flying mechanism.

In order to confirm the above, Fig. 6 shows a typical observed orbit of the model by 3D motion analysis, together with a parabolic orbit in free fall which is a free flight without fluid force. We should note that τ in Figs. 6 and 7 denotes the time which is zero at $x_E = 5$ m, while the model's release point is at $x_E = 0$ m.

Again, we can see that the observed orbit is approximated to be not an obvious parabolic curve but rather a straight line, after an initial instable and complicated curve. More specifically, the model is in an unstable and complicated flight, during an initial horizontal-flight-distance $x_E = 0 - 5$ m which corresponds to about three model's rotations after the model's release. Afterwards, the model becomes in a stable and approximately-straight flight at $x_E > 5$ m.

Complimentarily speaking, when we draw the parabolic orbit, we have to estimate the accurate values of model's flight-velocity components at $x_E = 5$ m where the beginning of the stable and approximately-straight flight is. Figure 7 shows the time series of flight-velocity components, during a duration $\tau = 0 - 0.3$ s which corresponds to a horizontal-flight-distance range of $x_E \approx 5$ m – 10 m with about three model's rotations. Figures (a) and (b) represent the horizontal component U and the vertical component W of the model's velocity vector, respectively. During this duration, we can confirm that both the components are approximated by straight lines. That is to say, $U = -2.5\tau + 15.9$ in figure (a), and $W = -0.7\tau + 2.2$ in figure (b). The parabolic orbit in Fig. 6 is calculated using the initial condition at $x_E = 5$ m by these formulae with $\tau = 0$.

Figure 8 also shows a result of field observations; namely, translation speed $U_\infty (\equiv (U^2 + W^2)^{1/2})$, angular velocity Ω and rotation parameter Ω^* are plotted against the horizontal flight distance x_E . Subscripts "1RA" and "3RA" denote the averages over one rotation and three rotations, respectively. We can see that Ω^* monotonically increases with increasing x_E , while both U_∞ and Ω monotonically decreases with increasing x_E . This suggests the decay of model's rotation is relatively smaller than that of model's flight speed.

Table 3 summarises dimensional and non-dimensional kinetic parameters obtained by field observations, which are ensemble averaged over 20 trials by plural persons. Of course, all the data in Table 3 are in the stable and approximately-straight flight after the initial instable and complicated flight. Then, we can confirm the reproducibility of this flight manner, although future improvements from a quantitative viewpoint using more trials by accurate equipment are desired. As a result, we can see that Re and Ω^* are about 10^3 and about 0.2, respectively.

3.2 Initial instable and complicated flight

Figure 9 shows the time series of model's posture at various x_E 's. More specifically, this figure indicates multiple-exposure photographs of a rotating pipe in flight. The centres of photographs (a), (b), (c) and (d) are at $x_E = 1$ m, 3 m, 5 m and 10m, respectively. In each photograph, a model flies in the direction of an arrow. We can see that the model flies fluctuating its posture upward, downward, left-ward and right-ward, remarkably at $x_E < 5$ m. The fluctuating amplitude of the posture decreases, as the horizontal flight distance x_E increases. Finally, the amplitude becomes almost zero at $x_E \geq 5$ m.

From Fig. 9, we get Fig. 10, namely, the time series of moment. We should note that τ in Figs. 10 and 11 denotes the time which is zero at $x_E = 1$ m, 3 m or 10 m. More specifically, we calculate the root-mean-square (RMS) values of angular-acceleration terms (open symbols in the figure), nonlinear terms (solid symbols) and external (fluid) moment terms (two crosses and one asterisk) in Eqs. (10) – (12), at $x_E = 1$ m, 3 m and 10 m. We omit the results at $x_E = 5$ m, because they are close to zero as well as the results at $x_E = 10$ m.

At first, we see the results at $x_E = 1$ m. The RMS of angular-acceleration terms is small and close to zero at any time. On the other hand, the RMS of nonlinear terms is much large than that of angular-acceleration terms, and fluctuates with time τ with a large amplitude. The RMS of external moment terms almost coincide with that of nonlinear terms. —To be exact, the RMS of external moment terms is slightly smaller than that of nonlinear terms.— This suggests that the nonlinear term (or the gyroscopic moment by model's rotation) is almost balanced to the external moment (or the aerodynamic fluid moment) at any time, and that the influence of model's angular acceleration upon angular momentum equilibrium is negligible. Second, we see the results at $x_E = 3$ m. From a qualitative point of view, the results are the same as those at $x_E = 1$ m. From a quantitative point of view, each RMS at $x_E = 3$ m is smaller than that at $x_E = 1$ m at any time. Finally, we see the results at $x_E = 10$ m. From a qualitative point of view, all the results are the same as those at $x_E = 1$ m and 3 m, again. From a quantitative point of view, each RMS at $x_E = 10$ m is much smaller than those at $x_E = 1$ m and 3 m at any time, then is close to zero.

Fig. 6 Observed orbit of a model, together with a parabolic one. τ denotes the time which has zero at $x_E = 5$ m.

Fig. 7 Time series of flight velocity at $\tau = 0 - 0.3$ s, which corresponds to a horizontal flight distance of $x_E \simeq 5 - 10$ m with about 3 model's rotations.

Fig. 8 Translation speed $U_\infty (\equiv (U^2 + V^2)^{1/2})$, angular velocity Ω and rotation parameter Ω^* versus horizontal flight distance x_E . Subscripts “1RA” and “3RA” denote the average over one rotation and three rotations, respectively.

	Table 3 Summary of field observation.	
	Commercial model (X-zyLo™)	Model (simplified)
Translation speed U_∞	16.9 m/s	14.8 m/s
Angular velocity Ω	60.3 rad/s	55.7 rad/s
Reynolds number $Re (= Re(t))$	1100	970
(Reynolds number $Re(d)$ based on d)	(110,000)	(97,000)
Rotation parameter Ω^*	0.17	0.18

In summary, the gyroscopic moment is almost balanced to the external moment (or the aerodynamic fluid moment) at any time, and the influence of model's angular acceleration upon angular momentum equilibrium is negligible. In addition, as the horizontal flight distance x_E increases, both the itself value and the amplitude of RMS's become small to zero. During such a decaying and stabilising process, the gyroscopic effect plays a primary role balancing not angular acceleration of the model but aerodynamic fluid moment.

Supplementarily speaking, we can confirm a good correspondence between Figs. 9 and 10. The RMS of nonlinear term, tends to decrease with increasing x_E from 1m to 10 m in Fig. 10, and the variation of model's altitude tends to become small with increasing x_E from 1m to 10 m in Fig. 9. More specifically, at $x_E = 1$ m, the RMS of nonlinear terms at $\tau = 0.00375$ is smaller than those at $\tau = -0.01125$ and 0.01125 . Actually in Fig. 9(a), we can confirm that the model's altitude at $x_E = 0.95$ m – 1.15 m seems smaller than those at $x_E = 0.65$ m – 0.85 m and $x_E = 1.15$ m – 1.35 m. As well, at $x_E = 3$ m, the RMS of nonlinear terms at $\tau = 0.0075$ is smaller than that at $\tau = -0.0075$. Actually in Fig. 9(b), we can confirm that the model's altitude at $x_E = 3.07$ m – 3.20 m seems smaller than those at $x_E = 2.80$ m – 2.93 m.

Fig. 9 Time series of model's flight attitude. A model flies in the direction of an arrow.

Fig.10 Time series of moment.

3.3 Stable and approximately-straight flight

Figure 11 shows the time series of lift coefficient C_L and drag coefficient C_D at $x_E = 10$ m which are specified by 3D motion analysis based on the field observation for $Re = 1,020$, $\Omega^* = 0.19$ and an attack angle $\alpha = 2^\circ$. Strictly speaking, x_E at $\tau = 0$ is equal to 10 m. In each figure, the time-mean value of 3D motion analysis is denoted by a solid line, namely, $C_L = 0.105$ in figure (a) and $C_D = 0.043$ in figure (b). Figures (a) and (b) represent C_L and C_D , respectively. Such a fact as $C_L = 0.105$ leads almost the same value of lift L as gravity mg . This balance between L and mg is a fundamental mechanism of the straight flight.

And in each figure, we provide some theories for reference, namely, a 2D-wing potential theory (for aspect ratio $AR = \infty$), a high-aspect-ratio-wing potential theory (for $AR > 5$) and a slender-body potential theory (for $AR < 1$) in figure (a), and a laminar-boundary-layer theory and a slender-body potential theory in figure (b). In these theories except for the laminar-boundary-layer theory, we assume a bi-plane which is a pair of parallel rectangular flat plates with a span of d and a length of l . In the 2D-wing potential theory, C_L is $2\pi\sin\alpha$ by the Kutta-Joukowski theorem such as $L = -\rho U_\infty \Gamma$ together with such a flat-plate circulation as $\Gamma = -4\pi U_\infty (l/4)\sin\alpha$ (Kutta, 1902 and Joukowski, 1906 quoted from Lamb, 1932). In the high-aspect-ratio-wing potential theory, C_L is given by Anderson (1936) who proposed such a formula as

(a) Lift coefficient C_L

(b) Drag coefficient C_D

Fig. 11 Time series of lift coefficient C_L and drag coefficient C_D at $x_E = 10$ m (for $Re = 1,020$, $\Omega^* = 0.19$ and $\alpha = 2^\circ$).

$\partial C_L / \partial \alpha = 2\pi / (1 + 2\pi / (\pi AR))$. In the slender-body potential theory, C_L and C_D are given by Jones (1946) and Wu (1971) who proposed such formulae as $C_L = (1/2) \pi AR \alpha$ and $C_D = (1/2) C_L \alpha$. In the laminar-boundary-layer theory, D is given by $0.664(\mu \rho U_\infty^3 l)^{1/2} \times \pi d \times 2$ (Blasius, 1908) where we assume viscous force acts over both inside and outside surfaces of a pipe. While these theories intrinsically provide us instantaneous C_L 's and C_D 's depending on time, Fig. 11 also shows both time-mean C_L and C_D using time-mean values of U_∞ and $\alpha (= 2^\circ)$.

At first, we see figure (a). C_L is almost constant to 0.105 (time-mean value), with a negligible perturbation, being independent of time. This small perturbation suggests good accuracy in the measurement of C_L . In addition, although the 2D-wing potential theory is so far from the observed result of 0.105, both the high-aspect-ratio-wing potential theory and slender-wing potential theory are rather close to the observed one. In summary, lift force of the model could be predicted by three-dimensional-wing potential theories.

Second, we see figure (b). The time-mean value of C_D equals 0.043 and is close to zero, while the amplitude of C_D 's perturbation suggests poor accuracy in the measurement of C_D in contrast with that in C_L . This poor accuracy could be because of a much larger velocity component U in the model's flight direction than those V and W in its normal directions. Then, the absolute value of V 's error tends to become much larger than that of W 's error, at each instant. And, Eqs. (7) and (9) suggest $\dot{U}$ and $\dot{W}$ are dominant over C_D and C_L , respectively. In future, we need more precise measurements of C_D for further discussion on mechanism. However, as well as field observation, both the theories suggest that drag force of the model is very small and close to zero.

Fig. 12 Streamlines for $Re = 1,020$, $\Omega^* = 0.19$ and $\alpha = 2^\circ$. Blue lines indicate streamlines.

Fig. 13 Influence of model's rotation: simulated orbit on the basis of computed C_L . τ denotes the time which has zero at $x_E = 5$ m.

3.4 Influence of model's rotation

In this subsection, we discuss the influence of model's rotation upon its flight. In general, it is difficult to realise an ideal condition in experiment, but rather easy to do it in computation. Now, we conduct numerical simulations, and reveal the flow in the same condition as the field observations' one in the preceding subsection.

Figure 12 shows streamlines for $Re = 1,020$, $\Omega^* = 0.19$ and $\alpha = 2^\circ$. All these values of Re , Ω^* and α coincide with the time-mean values in Fig. 11. In this condition, the present numerical simulation reveals that $C_L = 0.104$, which is close to 0.105 by the field observation in Fig. 11. This suggests good accuracy in the present numerical simulation.

In the figure we can see that the flow is everywhere uniform, steady and laminar with neither turbulence nor flow separation, except for a very-narrow wake of the model. This supports such a conclusion as three-dimensional potential theories give good approximations on lift force in Fig. 11(a), because the flow in Fig. 12 is nearly the velocity-potential flow past the model.

The flow for $Re = 1,020$, $\Omega^* = 0.19$ and $\alpha = 2^\circ$ is almost the same as that in Fig. 12. Rigorously speaking, we can find out a slight discrepancy just near the model's back face in the very-narrow wake where the model's rotation induces relatively-small azimuthal-velocity component. In addition, $C_L = 0.110$ in this condition, which is close to 0.104 by the computation for $\Omega^* = 0.19$ and 0.105 by the field observation in Fig. 11. In summary, the flow in the stable and approximately-straight flight is nearly the velocity-potential one. And, we could ignore the influence of model's rotation upon the flow.

In order to confirm this conclusion, we again consider model's orbit as well as Fig. 6. Figure 13 shows the influence of model's rotation upon its orbit. More specifically, this figure indicates two simulated orbits on the basis of computed C_L , together with both the observed orbit and the parabolic orbit in Fig. 6. The initial condition at $x_E = 5$ m of the simulated orbits is the same as that of the parabolic orbit based on Fig. 7. One simulated orbit is for $\Omega^* = 0.19$ (in rotation), and the other simulated orbit is for $\Omega^* = 0$ (in no-rotation). Both the simulated orbits supposing fluid force are close to the observed one, and much different from the parabolic orbit which is the simulated orbit without any fluid force. That is to say, we cannot ignore fluid force in the model's orbit, and can ignore the influence of model's rotation in addition to confirming the accuracy of numerical analysis.

4 Conclusions

We have investigated such a model as a rotating pipe in flight by field observation and numerical analysis. Obtained results are as follows.

- (1) The observed orbit is approximated to be not an obvious parabolic curve but rather a straight line, after an initial instable and complicated curve. The stable flight with this approximately-straight orbit suggests the importance of aerodynamics in flying mechanism. More specifically, the model is in an unstable and complicated flight, during an initial horizontal-flight-distance $x_E = 0 - 5$ m. Afterwards, the model becomes in a stable and approximately-straight flight at $x_E > 5$ m. In the stable and approximately-straight flight after the initial instable and complicated flight, the decay of model's rotation is relatively smaller than that of model's flight speed, and the Reynolds number Re and the rotation number Ω^* are about 10^3 and about 0.2, respectively.
- (2) In the initial instable and complicated flight at $x_E < 5$ m, the model flies fluctuating its posture upward, downward, left-ward and right-ward. As the horizontal flight distance x_E increases, both the absolute value and the amplitude of moment become small to zero. During such a decaying and stabilising process, the gyroscopic effect plays a primary role balancing not angular acceleration of the model but aerodynamic fluid moment.
- (3) In the stable and approximately-straight flight, we reveal aerodynamic characteristics on the basis of field observation. That is to say, such a fact. In addition, lift force of the model could be predicted by three-dimensional-wing potential theories, while the drag force of the model is very small and close to zero as well as theories.
- (4) The flow in the stable and approximately-straight flight is nearly the velocity-potential one. And, we could ignore the influence of model's rotation upon flow, orbit and so on. In this context, model's rotation is only to stabilise its posture, and gives negligible contribution upon its aerodynamics.

In future, we need more precise measurements for further discussion on mechanism together with more modulus in experiments for better reliability and repeatability, by which we could innovate curious flying/swimming machines.

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