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Analysis of Flow around a Flying Pipe

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Abstract

The present aim is to reveal the flow past a rotating pipe which is immersed parallel to the mainstream. At first, we conduct field observations of a flying pipe using a pair of high-speed video cameras, together with motion analyses based on their recorded images, which quantitatively reveal both paths and angular velocities of the flying pipe. In addition, we conduct numerical simulations by a finite difference method, whose results suggest that the pipe-rotation effect becomes remarkable for a rotation parameter $\Omega^* > 0.4$.

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1. Introduction

The present study concerns the aerodynamics of a flying pipe in rotation, with which we might be familiar as “X-zylo [1].” Some flying pipes could fly faster than such a similar projectile as a flying disc or “Frisbee,” and farther than a football. The flying disc is very popular not only as a toy, but also as an instrument of such games as Ultimate, Disc golf, Guts, Crosbee, 500, Disc dog, Flying disc freestyle, Fricket, Double disc court, Friskee, Durango boot, Flutterguts, Kan-jam and so on. At present, games using the flying pipe have not been established well, and it’s only application is for a toy. However, the flying pipe could have the potential for a projectile-sports instrument, as well as the flying disc.

From an aerodynamic point of view, both the flying pipe and the flying disc are regarded as bluff bodies, namely, non-streamline-shaped bodies. However, the flow past such a bluff body at higher 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. Among bluff-body problems, there have been less research concerning three-dimensional ones. As three-dimensional basic studies, it seems appropriate to consider axisymmetric bodies with simple geometries like a sphere and a disc, whose knowledge are required in the analyses of many flying or suspended objects in fluid. But, even the flow past such a simple axisymmetric body has not been revealed enough in comparison with such a two-dimensional body as a circular cylinder, despite of wide ranges of it’s applicabilities. A pipe or a tube is another simple axisymmetric bluff body. And, researches on the flow past a pipe 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 flow meters, as well as flying toys. Although there have existed few researches on the flow past a pipe, we can find several researches on the flow past a ring, a torus or a washer, which is not in rotation but stationary [2] – [8]. Recently, the flow has attracted our attention in the context of a new-concept wind-mill design [9].

The present aim is to reveal the flow past a rotating pipe which is immersed parallel to the mainstream. At first, we conduct field observations of a flying pipe in rotation using a pair of high-speed video cameras, together with motion analyses based on their recorded images, which quantitatively show both paths and angular velocities of the flying pipe. In addition, we conduct numerical simulations by a finite difference method based on the MAC scheme.

2. Method

2.1. Model and Parameters

Figure 1a shows the present flying-pipe model: namely, a rotating pipe in uniform flow. In addition, Fig. 1a also shows the present coordinate system, which is a cylindrical one (r, θ, z) with its origin O at the front centre.

Governing geometric parameters in non-dimensional forms are a reduced pipe’s thickness $t/d$ and a reduced pipe’s length $l/d$, where the model’s dimensions $d$, $l$ and $t$ denote the mean diameter, the length and the thickness of the pipe, respectively. $t/d$ and $l/d$ are defined as follows.

$$\frac{t}{d} = \frac{d_o - d_i}{d_o + d_i}$$

and

$$\frac{l}{d} = \frac{2l}{d_o + d_i},$$

where $d_o$ and $d_i$ denote the outer and inner diameters of the model, respectively.

A governing kinetic parameters in non-dimensional forms are the Reynolds number $Re$ and a rotating parameter $\Omega'$. $Re$ is defined by

$$Re = \frac{U_\infty t}{\nu},$$

where $U_\infty$ and $\nu$ denote the mean flow velocity of a uniform mainstream and the kinetic viscosity of fluid, respectively. If we regard $d$ instead of $t$ as a characteristic length scale, we define another Reynolds number $Re(d)$ based on $d$, given by

$$Re(d) = \frac{U_\infty d}{\nu}.$$ 

$\Omega'$ is defined by

$$\Omega' = \frac{d}{2} \Omega / U_\infty,$$
where $\Omega$ denotes the angular velocity of pipe’s rotation. Then, $\Omega^*$ represents the ratio of pipe’s rotating velocity at the outer diameter to flow velocity of the mainstream.

The base pressure $p_b$ measured at the centre of pipe’s back face and the predominant frequency $f$ of $p_b$ are non-dimensionalised as a base suction coefficient $-C_{pb}$ and the Strouhal number $St$, respectively. Their definitions are as follows.

$$St = \frac{f t}{U_{\infty}}$$

and

$$-C_{pb} = -\frac{(p_b - p_\infty)}{1/2 \rho U_{\infty}^2},$$

where $p_\infty$ and $\rho$ denote the static pressure in the mainstream and the density of fluid, respectively.

2.2. Field Observation

Figure 1b shows 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). Two cameras are synchronised with each other by a trigger-pulse generator (No. 3). Two personal computers (No. 4) are connected to the cameras by IEEE1394, in order to initialise/monitor the cameras and storage/analyse the recorded data. For calibration of the present stereo system, we use four colour corns (No. 5).

2.3. Numerical Analysis

In many actual situations, most of the flow at $Re < 10^6$ 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 the MAC method in a finite-difference scheme, a third-order-upwind difference method in spatial discretisation of convective terms, a second-order-central difference method in spatial discretisation of the other terms, and the Euler explicit method in a time marching.

As a spatial grid, we use a regular cylindrical grid with unequal spacing, as shown in Fig. 3. The grid numbers in the $r$, $\theta$ and $z$ directions are 150, 42 and 105, respectively. The minimum grid size $\Delta r_{\min}$, $\Delta \theta$ and $\Delta z_{\min}$ are 0.14$t$, 0.05$\pi$ rad and 0.20$t$, respectively. Computational-domain sizes in the $r$ and $z$ directions are 58$t$ and 26$t$, respectively. The former is equal to 10$d$/2, and the latter is equal to 22$l$. Such computational parameters as the grid and computational-domain sizes are determined by many preliminary trials, to achieve negligible influences upon results.

![Fig. 1](image-url)
The boundary conditions on the pipe’s surfaces are viscous. On the outer boundaries of the computational domain, we suppose the Dirichlet condition; that is, $v_r = 0$, $v_\theta = 0$ and $v_z = U_c$.

At a time step $\Delta t = 1.0 \times 10^{-4}/U_c$, we proceed with these time-marching computations. During the computations, we monitor the value of $-C_{pb}$ to judge whether the total computation time is enough or not for fully-saturated conditions.

3. Results and discussion

3.1. Field observation

Figure 2a shows an example of field observations; namely, an instantaneous image obtained by a high-speed video camera. The model flies from the right to the left. We can see that an orbit of the model is approximated to be rather a horizontal straight line, not an obvious parabolic curve.

Table 1 summarises typical dimensions and observed data of the model, together with non-dimensional geometric and kinetic parameters for the field observation. The non-dimensional geometric parameters are as follows: $t/d = 0.01$ and $l/d = 0.5$. And, the obtained non-dimensional kinetic parameters are as follows: $Re \approx 500$ ($Re(d) \approx 50000$) and $\Omega' \approx 0.15$.

3.2. Numerical simulation

Table 2 summarises non-dimensional geometric and kinetic parameters of the model for numerical analysis. $Re$ is fixed to $1.0 \times 10^2$, and the tested range of the rotation parameter $\Delta \Omega'$ is $0 - 1.2$. We should note that the model is not in rotation for $\Delta \Omega' = 0$.

Figure 3a shows time histories of the base suction coefficient $-C_{pb}$ for several values of $\Delta \Omega'$. At first, we see the result for $\Delta \Omega' = 0.0$ (in non-rotational motion). At the time enough after the start-up of computation (at $\tau U_c/t \geq 100$), $-C_{pb}$ becomes periodic being independent of initial conditions. As will be shown in flow visualisation such as Fig. 5, this periodicity is related with an alternate shedding of ring-like vortices from the model’s inside and outside. Next, we see the results for $\Delta \Omega' \neq 0.0$ (in rotational motion). We can confirm the same periodicity as that for $\Delta \Omega' = 0.0$. However, we can also confirm some effects of $\Delta \Omega'$ from a quantitative point of view: that is, the time histories are not identical one another for different values of $\Delta \Omega'$. So, we discuss the $\Delta \Omega'$ effects, next.

We examine some $\Delta \Omega'$ effects in Figs. 3b, 4a and 4b. At first, Fig. 3b shows a time-mean base suction coefficient $\left(-C_{pb}\right)_{\text{mean}}$ versus $\Delta \Omega'$. We can see that $\left(-C_{pb}\right)_{\text{mean}}$ monotonically increases with increasing $\Delta \Omega'$. More specifically, for $\Delta \Omega' > 0.4$, $\left(-C_{pb}\right)_{\text{mean}}$ becomes obviously larger than that for $\Delta \Omega' = 0.0$. For reference, Fig. 3b also shows a formula $0.274 + (\Omega')^2$ by a dashed line, and another formula $0.274 + (C_{BS} \Omega')^2$ with an empirical coefficient $C_{BS} = 0.15$. In the former, we consider resultant velocity of the mainstream and the model’s rotation. Much larger $\left(-C_{pb}\right)_{\text{mean}}$ by this theory suggests a nonlinearity of the flow. The latter is a modified one using $C_{BS}$.

Fig. 2. (a) Computational grid; (b) An example of field observation; an instantaneous image by a high-speed video camera. A model flies from the right to the left.
Table 1. Model’s dimensions and observed data, together with geometric and kinetic parameters for field observation

| Parameter                      | Value   |
|-------------------------------|---------|
| Diameter \( d \)              | 0.1 m   |
| Thickness \( t \)              | 0.001 m |
| Length \( l \)                 | 0.05 m  |
| Reduced thickness \( t/d \)   | 0.01    |
| Reduced length \( l/d \)      | 0.5     |
| Translation distance per a rotation | 1.8 m |
| Angular velocity \( \Omega \) | 30 rad/s |
| Translation speed \( U_r \)    | 8.0 m/s (30 km/h) |
| Reynolds number \( Re \)      | 500     |
| (Reynolds number \( Re(d) \) based on \( d \)) | 50000 |
| Rotation parameter \( \Omega^* \) | 0.15 |
| (Pipe-edge-velocity ratio)     |         |

Table 2. Model’s geometric and kinetic parameters for numerical analysis.

| Parameter                      | Value   |
|-------------------------------|---------|
| Reduced thickness \( t/d \)   | 0.16    |
| Reduced length \( l/d \)      | 0.2     |
| Reynolds number \( Re \)      | 100     |
| (Reynolds number \( Re(d) \) based on \( d \)) | 600 |
| Rotation parameter \( \Omega^* \) | 0 – 1.2 |
| (Pipe-edge-velocity ratio)     |         |

Second, Fig. 4a shows a non-dimensional base-suction amplitude \( (-C_{pb})_{max} - (-C_{pb})_{min} \) versus \( \Omega^* \). We can see that \( (-C_{pb})_{max} - (-C_{pb})_{min} \) tends to keep a constant of 0.08, being independent of \( \Omega^* \), in contrast to Fig. 3b.

Thirdly, Fig. 4b shows the Strouhal number \( St \) versus \( \Omega^* \). As well as Fig. 3b, \( St \) monotonically increases with increasing \( \Omega^* \). More specifically, for \( \Omega^* > 0.4 \), \( St \) becomes obviously larger than that for \( \Omega^* = 0.0 \). For reference, Fig. 4b also shows a formula \( 0.113(1 + (\Omega^*)^2) \) by a dashed line, and another formula \( 0.113(1 + (C_{ST}\Omega^*)^2) \) with an empirical coefficient \( C_{ST} = 0.1 \) by a chained line. Both the former and the latter are defined as well as Fig. 3b. Again, much larger \( St \) by the former suggests a nonlinearity of the flow.

Finally, Fig. 5 shows typical visualised flows and reveal velocity vectors and pressure distribution at \( \Omega^* = 0.0, 0.4, 0.8 \) and 1.2, respectively. We can see that all those flows are characterised by alternative
shedding of ring-like vortices from the model’s inside and outside, and that they are very similar one another despite of different values of $\Omega'$.

Fig. 5. Velocity vectors and pressure distribution, (a) for $Re = 100$ and $\Omega' = 0.0$ at $\tau U_0/t = 151$, (b) for $Re = 100$ and $\Omega' = 0.4$ at $\tau U_0/t = 15$ (c) for $Re = 100$ and $\Omega' = 0.8$ at $\tau U_0/t = 150$, and (d) for $Re = 100$ and $\Omega' = 1.2$ at $\tau U_0/t = 149$

4. Conclusions

In order to reveal the flow past a rotating pipe which is immersed parallel to the mainstream, we conduct field observations of a flying pipe in rotation using a pair of high-speed video cameras, together with motion analyses based on the recorded images, which quantitatively show both paths and angular velocities of the flying pipe, and the values of main kinetic parameters. In addition, we conduct numerical simulations by a finite difference method based on the MAC scheme, whose results suggest that the pipe-rotation effect becomes remarkable for a rotation parameter $\Omega' > 0.4$.

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