Establishing a Cyclone Gyro Model to Study the Trajectory of Tornadoes

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Abstract: This paper attempts to study the rotation and advance characteristics of tornadoes by experiments and theoretical analysis. A cyclone generator that simulates the characteristics of tornado is completed, and put to experiments under different wind fields in the wind tunnel laboratory. The rotation pattern and advance pattern are analyzed from both the Bernoulli Principle and precession principle. Finally, this paper makes a summary of the research done so far and puts forward the prospect of the next experiment.

1. Introduction
The formation of the tornado is related to complicated meteorological conditions such as atmospheric temperature, humidity, and airflow disturbances[1]. A tornado upon its formation travels on the ground under the effect of an atmospheric wind field[2]. The prediction of tornado trajectory has always been a difficult problem concerned by scientists since the tornado could bring destruction and hazards to the areas where it passes by in its moving process. In this study, analysis of data from NOAA’s Storm Prediction Center found that the frequency and average intensity have an increasing tendency. The statistics have been charted and shown in Figure 1 and 2.

![Fig 1. The amount of tornadoes in the US (1950-2018)](image-url)
Mechanical devices can be used in experiments to study the flow-field of tornadoes[3,4]. A plurality of successful tornado simulators have been studied[5-7]. After consulting fluid dynamics laws[7-9], we built a new tornado simulator which has the necessary characteristics of a tornado. Not only can it produce a stable wind field, but also move freely on an experiment platform of water. In this study, problems of the tornado's travel path are explored in a wind tunnel, where the wind field of the tornado is simulated and its travel path is observed in the laboratory, through combining theoretical analysis with experiments. Valuable experimental data and theoretical deductions have been acquired for addressing practical problems.

2. Research Contents and Methods

According to the Bernoulli effect, the fluid velocity is in negative correlation to the intensity of pressure. Under the effect of an external wind field, the tornado might suffer unbalanced forces in its horizontal direction due to uneven flow velocity in the boundary layer, result in moving toward a certain direction. Meanwhile, since a rotating body may generate precession after receiving an external torque, precession might occur in the travel course of the tornado affected by the torque of the external wind field. This research aims to unveil the link between the wind velocity of the environment, the rotating speed of the cyclone and its trajectory. During the research, a cyclone generator for tornado simulation is made to verify the above speculations, and then the trajectories in the experiments are recorded and analyzed according to fluid dynamics laws.

Major research contents include:

1. Production of the cyclone generator.

The device designed by Zeng[10] consists of a clockwise air impeller rotation system, a floating support base, a counterclockwise water impeller rotation system, power source, and a controller. Specifically, the clockwise air impeller rotation system includes an air impeller assembly, a rotating drive motor of the air impeller, and a rotating main shaft of the air impeller. Each pair of impellers of the air impeller assembly is fixed at different heights of the air impeller rotating main shaft, and an updraft can be generated by the blade of the impeller in clockwise rotation. The lower end of the air impeller rotating main shaft is fixed to the rotating shaft of the air impeller rotating drive motor. The counterclockwise underwater impeller rotation system consists of an underwater impeller, an underwater impeller rotating drive motor, and an underwater impeller rotating main shaft. The underwater impeller is fixed to the lower end of the underwater impeller rotating main shaft, and the upper end of the impeller is fixed to the rotating shaft of the underwater impeller rotating drive motor. The schematic diagram and the structural diagram of the device are shown in Fig 3 and Fig 4.
2. Observation of the travel path of a tornado.

It's found that a funnel-shaped updraft field rotating clockwise can be produced by the tornado simulator upon observing the wind field of the tornado simulator with the hot-wire anemometer. The simulator is placed on the water surface in a floating state, which can simulate the travel path of a tornado. The travel law of the tornado can be systematically tested or simulated through changing a variety of test parameters, such as rotating velocity, and wind velocity in the wind field.

3. Measurement of Trajectories of the Cyclone Generator in the Wind Field

The velocity of the incoming air flow in the wind tunnel and the rotation velocity of the cyclone generator are two major variables used in the experiment. The influence of these two variables on travel path of the cyclone generator has been analyzed respectively in the data processing process. The blades of the cyclone generator rotates clockwise while looking down from the top. Three repeated experiments are performed in each situation of the experiment to lower the influence of random errors in the experiment. And the mean value of the three repeated experiments is taken for data analysis. Travel path images of the cyclone generator at different wind velocities of the incoming flow are shown in Fig 5.
Fig 5. Travel paths of the cyclone generator at different wind velocities of the incoming flow

As can be seen clearly from the experimental result, apparent and regular deflections are produced upon the operation of the cyclone generator under the effect of the external wind field. The control group with the non-rotating cyclone generator basically moves forward in a straight line. It can be concluded that the faster the cyclone generator motor rotates, and the stronger the simulated cyclone wind field, the more it moves towards the positive direction of the Y axis. The mean displacement in the positive direction of the Y axis of the quickly rotating group of the cyclone generator is 417mm. The mean displacement in the positive direction of the Y axis of the slowly rotating group of the cyclone generator is 273mm. And the mean displacement in the positive direction of the Y axis of the blade non-rotating group of the cyclone generator is 37mm. When the wind velocity of the incoming flow is ranged from 2.4m/s to 5.2m/s, the quickly rotating group of the motor will not be significantly affected by the wind velocity of the incoming flow. When the wind velocity of the incoming flow is 5.9m/s, the deflections of all groups are small. A likely cause is that the time it takes to reach the other side of the water tank is too short to generate the deflection.

4. Cause Analysis of Experimental Phenomena

Under the uniform external wind field, when the cyclone simulator blade is not rotating, the simulator moves forward along a straight line. When the cyclone simulator blade is rotating, it always has an obvious tendency to move forward and to the left. The phenomenon should be analyzed from the perspective of fluid dynamics. The Bernoulli principle and the precession principle are considered as underlying causes of this phenomenon in this study.

4.1. Bernoulli Principle

The force analysis of the cyclone generator in motion is shown in Fig. 6. Under the effect of the wind velocity of the incoming flow, the cyclone generator will receive the force \( F_X \) parallel to the direction of the incoming flow, and then move in the + X direction. The blades of the cyclone generator rotate clockwise while looking down from the top. The linear velocity of the blade in the + Y direction is consistent with the direction of the wind velocity of the incoming flow, while the linear velocity of the blade in the -Y direction is opposite to the direction of the wind velocity of the incoming flow. Thus, the air velocity of the cyclone generator in the + Y direction is greater than the air velocity in the -Y direction of the cyclone generator. According to the Bernoulli’s equation in the fluid mechanics:

\[
p + \frac{1}{2} \rho v^2 + \rho gh = C
\]

Since the air pressure at the cyclone generator + Y direction can be found to be smaller than that in the cyclone generator -Y direction, the combined force \( F_Y \) of the air pressure applying to the cyclone
generator in the Y direction points towards the + Y direction, that is, the cyclone generator will be shifted towards the right in its travel. The theoretical analysis conforms to the experimental results.

![Fig 6. Schematic diagram of the tornado](image)

Above is a schematic diagram of the tornado’s moving pattern, with an obvious offset direction of the travel course. In order to analyze factors affecting the offset, a theoretical analysis of the motion of the cyclone generator is conducted on the basis of certain simplification.

The wind velocity of the incoming flow, including the magnitude of the wind velocity of the incoming flow, the air density, and the Reynolds number, etc. of the incoming flow, and the structure and motion state of the cyclone generator, including the blade size, shape, position distribution, and velocity, etc. are major factors affecting $F_x$ and $F_y$. For the sake of convenience, air is regarded as incompressible fluid in theoretical analysis; air density is regarded as a constant $\rho = 1.29 \text{ kg/m}^3$; and the air viscosity coefficient is regarded as a constant $\mu = 1.983 \times 10^{-5} \text{ Pa} \cdot \text{s}$. Only the state of laminar flow is analyzed without considering the influence of turbulence. The cyclone generator can be simplified as a cylinder rotating at a certain angular velocity. The force under the effect of the wind field of the incoming flow is a problem concerning the flow around the asymmetric cylinder, as shown in Fig 7.

![Fig 7. Flow around the asymmetric cylinder](image)

From the principle of fluid mechanics, the flow function of the flow field of the flow around the asymmetric cylinder can be created by superposition of a flow function of the flow field of the flow around the symmetric cylinder and a vortex flow function[11], as shown in Fig.8.

![Fig 8. Superposition of flow around the cylinder and vortex flow around a symmetric cylinder](image)

The circulation $\Gamma$ of vortex is:

$$\Gamma = 2\pi\omega r^2$$  \hspace{1cm} (2)

$r$ is taken as the distance from an arbitrary point to the axis of cylinder rotation; and $\theta$ is the included angle of the line connecting an arbitrary point with the center of the cylinder and the direction of the...
incoming flow velocity in the polar coordinate system of Fig 10. In that case, the flow function corresponding to the flow around the symmetrical cylinder is:

\[ \Psi_1 = (V_r \sin \theta) \left(1 - \frac{R^2}{r^2}\right) \]  

The vortex-flow function is:

\[ \Psi_2 = \frac{\Gamma}{2\pi} \ln r + C \]

The total flow function can be obtained through superposition:

\[ \Psi = \Psi_1 + \Psi_2 = (V_r \sin \theta) \left(1 - \frac{R^2}{r^2}\right) + \frac{\Gamma}{2\pi} \ln \frac{r}{R} \]

The pressure coefficient corresponding to the cylinder surface is:

\[ C_p = 1 - \left(\frac{V_r^2}{V_c^2}\right) - 1 - \left(-2V_c \sin \theta - \frac{\Gamma}{2\pi R}\right)^2 \]

The lift (or the force on the cyclone generator in the + Y direction) is:

\[ F_L = q_\rho S C_D V_r V_c \rho \pi R V_R \]

The offset degree can be characterized by the ratio of velocities in both directions:

\[ \frac{V_r}{V_c} = k \frac{1}{1 + kt} \]

The result shows that \( V_r/V_c \) becomes greater with the increased offset degree when \( V_c \) is decreased or the angular velocity of motor rotation of the cyclone generator motor is increased, conforming to the law found in the experiment.

4.2. Precession

An analogy can be performed between the tornado's travel and the gyro's precession. A tornado is formed by rotating updrafts. If the cyclone within a certain rotating radius of the tornado is taken as the control volume, there are a cloud of gas with certain mass and angular velocity, being similar to a spinning gyro. When the axis of the gyro is not perpendicular to the ground, the gyro will be precessed under the influence of external torque such as gravity. In the situation shown in Fig 9, the precessed angular velocity is:
\[ \omega = \frac{\Delta F \times r}{L \sin \theta} \]  

(13)

Fig 9. Force analysis of the precessed gyro

The motion of the cyclone generator analyzed in the experiment is shown in Fig 10. Two sets of devices rotated in opposite directions are adopted in the experiment to reduce the possibility of the rotation of the cyclone generator cavity. The blade of the cyclone generator is rotated clockwise with its angular momentum in the downward direction; while the device with the lower part in reverse rotation is rotated counterclockwise with its angular momentum in the upward direction. Since the air resistance moment received by the upper air impeller is significantly greater than that of the lower reversing device, the direction of the overall angular momentum L might be upward. As the wind velocity of the incoming flow is horizontally to the right, the overall acting torque of the cyclone generator is also horizontally to the right. Based on the analysis of the precessed direction of the analog gyro, the cyclone generator will have a precession velocity Vprecession in the + Y direction in accordance with the right-hand rule, which is consistent with the overall velocity V to the left. By comparison, the analysis result conforms to the experimental result.

Fig 10. Analysis of the precession effect of the cyclone generator

5. Conclusion
An innovative cyclone generator that can float on the water with the air impeller rotating system is designed in this research to complement studies on tornadoes. A wind field of the tornado is simulated well through the cyclone generator. Meanwhile, external wind fields with different conditions are also applied in the wind tunnel. According to experimental results, the cyclone generator offsets to the left during the travel under the effect of the uniform external wind field. Moreover, the offset degree is positively correlated to the rotation velocity of the cyclone generator blade, and negatively correlated to
the magnitude of the wind velocity of the incoming flow. And it can be concluded that the analysis result conforms to the experimental result in accordance with the qualitative theoretical analysis conducted on the cyclone generator’s offset direction based on the Bernoulli’s equation. Furthermore, the motion of the cyclone generator in the uniform incoming flow is simplified into a problem of the flow around the asymmetric cylinder for the qualitative theoretical analysis, obtaining the influence of the wind velocity of the incoming flow and the blade rotation velocity on the magnitude of offset. By comparison, the analysis result conforms to the experimental result, which is rational.

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