On Finite Hurricane Disturbances and Hurricane Suppression by a Flying Spot

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***Abstract*—Based on previous author's publications [1, 2] the paper proposes space evaluations and effectiveness of hurricane suppression by wakes from flying aircraft(s).**

Keywords—hurricane; disturbances; aircraft, wake

I. INTRODUCTION

Tropical cyclones and their extreme cases, *hurricanes* (typhoons) are complicated natural thermo-aerodynamic machines working with a surprising efficiency and stability. They are the most dangerous phenomena for US and many other eastern countries like Japan, Korea, Philippines, and Northern Australia. The most damages to the US recently have been brought by the hurricane Katrina (2005). Hurricanes are created in near tropic zones and slowly propagate for several months along the warm sea currents. When arrived in inland they are destroyed, making plenty of damage. In the US, hurricanes come to the Gulf area from Atlantics, or propagate northern along the east Atlantic shore, or in the Eastern Pacific. But the latter under the season winds travel to the western open seas and present no danger.

The *structure* of a (quasi) stationary hurricane slowly propagating with a typical speed 4-6 mph in a horizontal direction is shown in Figure 1. Here in the central, *eye* area of diameter ~20-30 km, the air is almost still. Surrounding the eye region is the most active *eye wall* cylindrical area of ~20-30km of thickness. It has the highest rotational speed 100-200 mph and slow air ascends with the velocity 2mph with humid air transport till condensation level of about 2-3km high. This is the upper boundary of hurricane boundary layer (HBL). The rotating hurricane air is ascending to the tropospheric height of about ~20-22km and spreads in radial direction, causing heavy rains. Outside the eye wall region, there is only rotational flow, decaying inversely proportional to radius increase, with external hurricane radius, $r_a \sim 400-500$ km.

Because of impossibility of laboratory studies of hurricanes, only natural observations were possible. For a very long time the buyoffs have been used. Starting from 1960-s, specific reconnaissance aircrafts flying with a typical passenger speed ~ 700km/h have been employed. No fly accident has been reported. All experimental findings have been documented and published in numerous papers and several research monographs referred in [1, 2].

Several *theoretical* papers have also been published which explained few features of hurricane. However, the whole picture remained unclear until our recent publications [1, 2]. The essential feature of hurricanes making difficulty in their analysis is the high level interactions of its constituents. The first paper [1.1] in the series [1], published in the Los Alamos electronic journal (Atmospheric and Oceanic Physics division), presents introductory remarks with extensive literature review. The paper [1.2] analyzes the aeromechanics of non-isothermal air flow in upper part of hurricane, above the HBL. The third paper in the series analyses the most difficult problems of behavior of air flows in the HBL. They are complicated by evaporation from the ocean, back effects of surface waves generated by hurricane, and condensation at the upper boundary of the HBL. Finally, physical balance equations have been derived that allowed to close the theory. Using numerical examples, it was demonstrated that the approach was able to quantitatively describe all the phenomena found in observations. The final paper [1.4] in the series realistically described the most intriguing phenomena of hurricane occurrence ("genesis") and maturing. All these results have been presented by the author, invited to the Physical Science Division Seminar at NOAA in Boulder, CO (July, 2012), with no negative comments. The Seminar also suggested publishing the results in a journal. It was recently performed in paper [2]. .

Hurricane *suppression* has been proposed by many authors, most of them being not practical and even fantastic. In the author opinion, real proposal should satisfy the following three conditions: (i) practicality and simplicity, (ii) cost effectiveness and (iii) being not environmentally harmful. It was proposed in [3] hurricane suppression by flying supersonic jets with common speed more than 1200km/h, which create the boom wake. This proposal seemingly satisfied the above conditions. The rational here is to send the jets to destroy the most active hurricane zone – hurricane eye wall area in HBL, a cylinder about 100-120 km in diameter. Even with the velocity of jet close to the sound speed, the jet flying horizontally will overcome this distance for 5-10 minutes. Simple estimations established the size of moving spot from a single jet as ~ 15 km long (because of the jet effect) and 4 km in diameter; the speed of disturbance decaying linearly with distance in both directions. It means that several jets could completely destroy the hurricane structure in HBL on several levels.

II. HURRICANE EQUATIONS AND SPECIFICS

We will use below the common aerodynamic equations, suitable for the numerical studies of hurricane disturbances by flying aircraft. They are written in cylindrical coordinates as follows:

$$\mathbf{L}_{\rho} \equiv \partial_t(\rho r) + \partial_r(\rho r u_r) + \partial_\varphi(\rho u_\varphi) + \partial_z(\rho r u_z) = 0 \qquad (1_1)$$

$$\mathbf{L}_{\rho u_r} \equiv \partial_t(\rho r u_r) + \partial_r(\rho r u_r^2) + \partial_\varphi(\rho u_r u_\varphi) + \partial_z(\rho r u_r u_z) - \rho u_\varphi^2 = -r\partial_r p \qquad (1_2)$$

$$\mathbf{L}_{\rho u_\varphi} \equiv \partial_t(\rho r^2 u_\varphi) + \partial_r(\rho r^2 u_r u_\varphi) + \partial_\varphi(\rho r u_\varphi^2) + \partial_z(\rho r^2 u_z u_\varphi) = -r\partial_\varphi p \qquad (1_3)$$

$$\mathbf{L}_{\rho u_z} \equiv \partial_t(\rho r u_z) + \partial_r(\rho r u_r u_z) + \partial_\varphi(\rho u_\varphi u_z) + \partial_z(\rho r u_z^2) = r[\partial_z(p_a - p) + g(\rho_a - \rho)] \qquad (1_4)$$

Here the effect of Earth rotation on disturbances but on hurricane was neglected, and the adiabatic pressure-density relation in equations (1), was omitted. The operators $\mathbf{L}_{\rho}$ and $\mathbf{L}_{\rho u_i}$ defined in (1_1) - (1_4) will be used below.

The aim of this Section is to present the equations for evolution of disturbances and specify the flight of disturbing aircraft. The general approach is valid here with the following specifications for the velocity fields:

$$\underline{u}_0 = \{u_r^0, u_\varphi^0, u_z^0\}, \quad \underline{u}_f = \{u_r^f, u_\varphi^f, u_z^f\}, \quad \underline{u} = \{u_r, u_\varphi, u_z\} \quad (2)$$

Formulas (2) describe the finite disturbances in the velocity field.

The continuity equation for finite disturbances $\{\rho, \underline{u}\}$ is:

$$\partial_t(\rho r) + \partial_r(\rho r u_r) + \partial_\varphi(\rho u_\varphi) + \partial_z(\rho r u_z) = 0 \quad (3)$$

Here the $\{r, \varphi, z\}$ - components of momentum balance equation $\{\rho, u_\alpha u_r\}$ respectively are:

$$\mathbf{L}_{\rho u_r} + \partial_t[r(a_r + b_r)] + \partial_r(rQ_{rr}) + \partial_\varphi Q_{r\varphi} + \partial_z(rQ_{rz}) = -r\partial_r(\hat{p} - p_0 - p_f) + (\Delta\rho_0 + \Delta\rho_f)u_\varphi^2$$
$$+2u_\varphi \Delta\rho(u_\varphi^0 + u_\varphi^f) + 2u_\varphi(\rho_0 + \Delta\rho_f)(u_\varphi^0 + u_\varphi^f) + \Delta\rho_0(u_\varphi^f)^2 + \Delta\rho_f(u_\varphi^0)^2 + 2(\rho_0 + \Delta\rho_f)u_\varphi^0 u_\varphi^f \quad (4_1)$$

$$\mathbf{L}_{\rho u_\varphi} + \partial_t[r^2(a_\varphi + b_\varphi)] + \partial_r(r^2 Q_{r\varphi}) + \partial_\varphi(rQ_{\varphi\varphi}) + \partial_z(r^2 Q_{\varphi z}) = -r\partial_\varphi(\hat{p} - p_0 - p_f) \qquad (4_2)$$

$$\mathbf{L}_{\rho u_z} + \partial_t[r(a_z + b_z)] + \partial_r(rQ_{rz}) + \partial_\varphi Q_{\varphi z} + \partial_z(rQ_{zz}) = -r\partial_z(\hat{p} - p_0 - p_f) \qquad (4_3)$$

In equations $(4_1) - (4_3)$, the components of tensor $\underline{\underline{Q}}$ are presented in the form:

$$Q_{ij} = A_{ij}^{(1)} + A_{ij}^{(2)} + B_{ij} \quad (i, j = r, \varphi, z). \ (5)$$

Here $\underline{\underline{A}}_1, \underline{\underline{A}}_2, \underline{\underline{B}}$ are the Cartesian symmetric dyadic tensors in (4).

III. GENERAL DESCRIPTION

Consider the "flying spot" (the wake) caused by aircraft itself, flying along a prescribed trajectory $\underline{y}(t)$ in hurricane with a given speed $\underline{U}(t) = \dot{\underline{y}}(t)$. Let $\Re$, $\Omega_f(\underline{y}(t))$ be the regions occupied by hurricane and aircraft. Then the air flow region $\Omega = \Re / \Omega_f$ effectively consists of the large region of hurricane including the small region of flying spot, so Ω is the hurricane region except very small moved aircraft region $\Omega_f(\underline{y}(t))$.

$\forall \underline{x} \in \Omega$, the air flow is described by the aerodynamic equations of ideal gas with adiabatic assumption:

$$\partial_t \rho + \underline{\nabla} \cdot (\rho \underline{u}) = 0 \ , \ \partial_t (\rho \underline{u}) + \underline{\nabla} \cdot (\underline{u} \rho \underline{u}) = -\underline{\nabla} p \ , \ p / p_a^0 = (\rho / \rho_a^0)^\kappa \ ; \ \kappa = \gamma / (\gamma - 1) \approx 3.5 \quad (6)$$

In (6), the standard notations have been used with $\gamma \approx 1.4$ being the adiabatic exponent. Here p_a^0, ρ_a^0 are roughly considered as constants for standard unperturbed atmosphere on the sea level: $p_a^0 \approx 1000mb$, $\rho_a^0 \approx 1kg/m^3$.

Let $\hat{\underline{u}}$ and $\hat{p}(\hat{\rho})$ be actual velocity and pressure (density) fields in hurricane with flying aircraft in Ω , respectively. They can be presented as:

$$\hat{\underline{u}} = \underline{u}_0 + \underline{u}_f + \underline{u} \quad , \quad \hat{\rho} = \rho_a^0 + \Delta\rho_0 + \Delta\rho_f + \Delta\rho \quad , \quad \hat{p} = p_a^0 [1 + (\Delta\rho_0 + \Delta\rho_f + \Delta\rho) / \rho_a^0]^\kappa \quad (7)$$

Here the lower indexes "0" and "f" denote the known fields of unperturbed hurricane air flow and that in the flying spot, whereas $\underline{u}$ and ρ (p) stand for the finite disturbances in hurricane air flow caused by the flying aircraft.

The main assumptions:

1) The steady (quasi-steady) hurricane field is known as a solution of equations (6), whatever approximations to obtain them have been made. This field is:

$$\underline{u}_0(\underline{x}) \quad , \quad \rho_0(\underline{x}) = \rho_a^0 + \Delta\rho_0 \quad , \quad p_0(\underline{x}) = p_a^0 (1 + \Delta\rho_0 / \rho_a^0)^k \quad (8)$$

2) The unsteady flying spot field is known as a solution (6) of a special problem of wake behind moving aircraft, whatever approximations to obtain them have been made. This field is:

$$\underline{u}_f(\underline{x}, t) \quad , \quad \rho_f(\underline{x}, t) = \rho_a^0 + \Delta\rho_f \quad , \quad p_f(\underline{x}) = p_a^0 (1 + \Delta\rho_f / \rho_a^0)^k \quad (9)$$

In a good approximation, the field (9) is obtained numerically with account of undisturbed hurricane field (1); in a very rough approximation, the field (4) is numerically obtained by solving the problem of aircraft flow in the quiescent air.

IV. EQUATIONS FOR DISTURBANCES

We now present in the divergent form the equations of continuity and momentum balance for finite disturbances, which might be helpful for numerical analyses.

The density and pressure fields for finite disturbances are naturally defined as:

$$\rho = \rho_a^0 + \Delta\rho \ , \ p = p_a^0 [1 + \Delta\rho / \rho_a^0]^\kappa \ . \quad (10)$$

The equations for disturbances $\underline{u}(\underline{x}, t), \ \rho(\underline{x}, t)$ and/or $p(\underline{x}, t)$ are then obtained by substitution (2) into (4) with account of (3)-(5), and bearing in mind that the fields (8) and (9) are also the solutions of (4).

(1) The structure of *continuity equation* for finite disturbances can then be presented as:

$$\partial_t \rho + \underline{\nabla} \cdot (\rho \underline{u}) + \underline{\nabla} \cdot (\underline{a} + \underline{b}) = 0 \quad (11)$$

$$\underline{a}(\Delta\rho, \underline{u}) = \Delta\rho \cdot (\underline{u}_0 + \underline{u}_f) + (\Delta\rho_0 + \Delta\rho_f) \underline{u} \quad ; \quad \underline{b} = (\Delta\rho_f \underline{u}_0 + \Delta\rho_0 \underline{u}_f) \quad (12)$$

Here $\underline{a}$ is the "momentum amplifying factor". This is the vector linear in both density and velocity disturbances, dependent on the velocity and density disturbances of flying spot and undisturbed hurricane fields. Also, in (11), (12) $\underline{b}$ is the momentum force, the vector bilinear in the density disturbances and velocity fields of undisturbed hurricane and flying spot.

Thus the structure of (12) is seen as follows. The first two terms in the right-hand part are the common terms of continuity equation. The second terms are the disturbances presented here as the linear "amplifying" factor. It is caused by the pair interactions of flow and density disturbances with those for the flying spot and undisturbed hurricane. The last term in (12) is the "force" caused by the skew pair interaction of flying spot and hurricane density disturbances and corresponding airflows.

(2) The structure of *momentum balance equation* for finite disturbances can then be presented in the form:

$$\partial_t (\rho \underline{u}) + \underline{\nabla} \cdot (\underline{u} \rho \underline{u}) + \partial_t (\underline{a} + \underline{b}) + \underline{\nabla} \cdot (\underline{\underline{A}}_1 + \underline{\underline{A}}_2 + \underline{\underline{B}}) = -\underline{\nabla} (\hat{p} - p_0 - p_f) \quad (13)$$

Here $\hat{p}, p_0$ and p_f are presented in (2)-(4), the momentum amplifying factor $\underline{a}$ and momentum force $\underline{b}$ are given in (13). The linear and quadratic in disturbances symmetric tensor amplifying factors $\underline{\underline{A}}_1$ and $\underline{\underline{A}}_2$, and the symmetric tensor body force $\underline{\underline{B}}$ are given as:

$$\underline{\underline{A}}_1 = \{2\underline{u}(\underline{u}_0 + \underline{u}_f)(\rho_0 + \Delta\rho_f) + (\underline{u}_0 + \underline{u}_f)^2 \Delta\rho\}^S ; \ \underline{\underline{A}}_2 = \{\underline{u}\underline{u} \cdot (\Delta\rho_0 + \Delta\rho_f) + 2\Delta\rho \underline{u}(\underline{u}_0 + \underline{u}_f)\}^S$$

$$\underline{\underline{B}} = \Delta\rho_f \underline{u}_0 \underline{u}_0 + \Delta\rho_0 \underline{u}_f \underline{u}_f + 2(\rho_0 + \Delta\rho_f)\{\underline{u}_0 \underline{u}_f\}^S \quad (14)$$

Here upper symbol "S" means symmetrization of dyadics.

If the density disturbances are small enough i.e. $\Delta\rho/\rho_a^0, \Delta\rho_0/\rho_a^0, \Delta\rho_f/\rho_a^0 << 1$, then

$$\partial_i(\hat{p} - p_0 - p_f) \approx (p_a^0/\rho_a^0)\partial_i(\Delta\rho) \approx \partial_i p. \quad (15)$$

V. THE PROPOSED MECHANISM OF HURRICANE DESTROYING BY FLYING SUPERSOUND JETS

It is currently impossible to make *a priory* or scaling evaluations for disturbances, even if the basic fields of hurricane and flight are known. This is because the hurricane field is less intense but well spread, but the flight field is very intense but localized.

Nevertheless, rough estimates of far field decay in intensities of pressure and velocity from flying spot can be made.

Let E be the energy generated by aircraft. Then in the far field rough approximation, this energy decays at moving radius R from aircraft due to energy irradiation is:

$$E_R \approx El^2/(2\pi R^2) \quad (16)$$

Here l is a characteristic size (say, length) of aircraft, and we consider the energy radiation only trough the boundary of hemisphere behind the aircraft.

Using the rough estimate $E \sim \rho U^2/2 \square\ p$, where U is the aircraft speed, one can obtain from (16) the evaluations of pressure p_R and velocity U_R decay behind the flying aircraft at distance R as:

$$p_R \approx p_a l^2/(2\pi R^2),\ U_R \approx Ul/(R\sqrt{2\pi}). \quad (17)$$

Consider example of aircraft with length $l = 20m$. Then at the radius $R = 100m$, $p_R/p_a \approx 6.4\times10^{-3}$ and at radius $R = 500m$, we have $U_R/U \approx 1.6\times10^{-2}$. So with the aircraft speed $U \approx 600m/s$ one obtains $U_{500} \approx 10m/s$. This makes a good 20% distortion of the hurricane maximum speed 50*m/s*. At *R* = 2000 *m*, the velocity of disturbances is ~2.5 *m/s*. Thus the effect of aircraft wake is confined in an effective tube of diameter ~ 4*km*, and length of wake ~ 13 *km.* With the outer diameter of eye wall jet about 60 km, the wake propagates through the active area of hurricane for ~ 100 sec, highly increasing the speed of air, and destroying the hurricane structure. Two or three aircrafts flying on various levels can completely destroy the hurricane for about tens of minutes.

This is the proposed *mechanism of hurricane destroying* by flying super sound jets.

Remarks

1. In numerical simulations, the aircraft should perform almost circular flight with a constant rotating speed U along the almost circular trajectory, $\varphi = \varphi_0 - (U/r_f)t$, slightly inclined by the angle $\alpha = (1\text{-}2)^0$ down to the horizon, with the initial height h_f.

2. The flight should be performed in the anti-cyclonic direction, i.e. against the direction of local Earth rotation or against the rotating hurricane angular velocity.

3. Parameters r_f, h_f and α could be considered as optimal control parameters for optimizing the effects of aircraft on hurricane destroying. It seems that $h_f < h_b$ and $r_f < r_0$, where h_b is the height and r_0 is the external radius of eye wall in boundary layer of hurricane.

4. A possible "turbulent" effects could be included in the simulations with realistic (empirical) turbulent viscosity coefficient(s).

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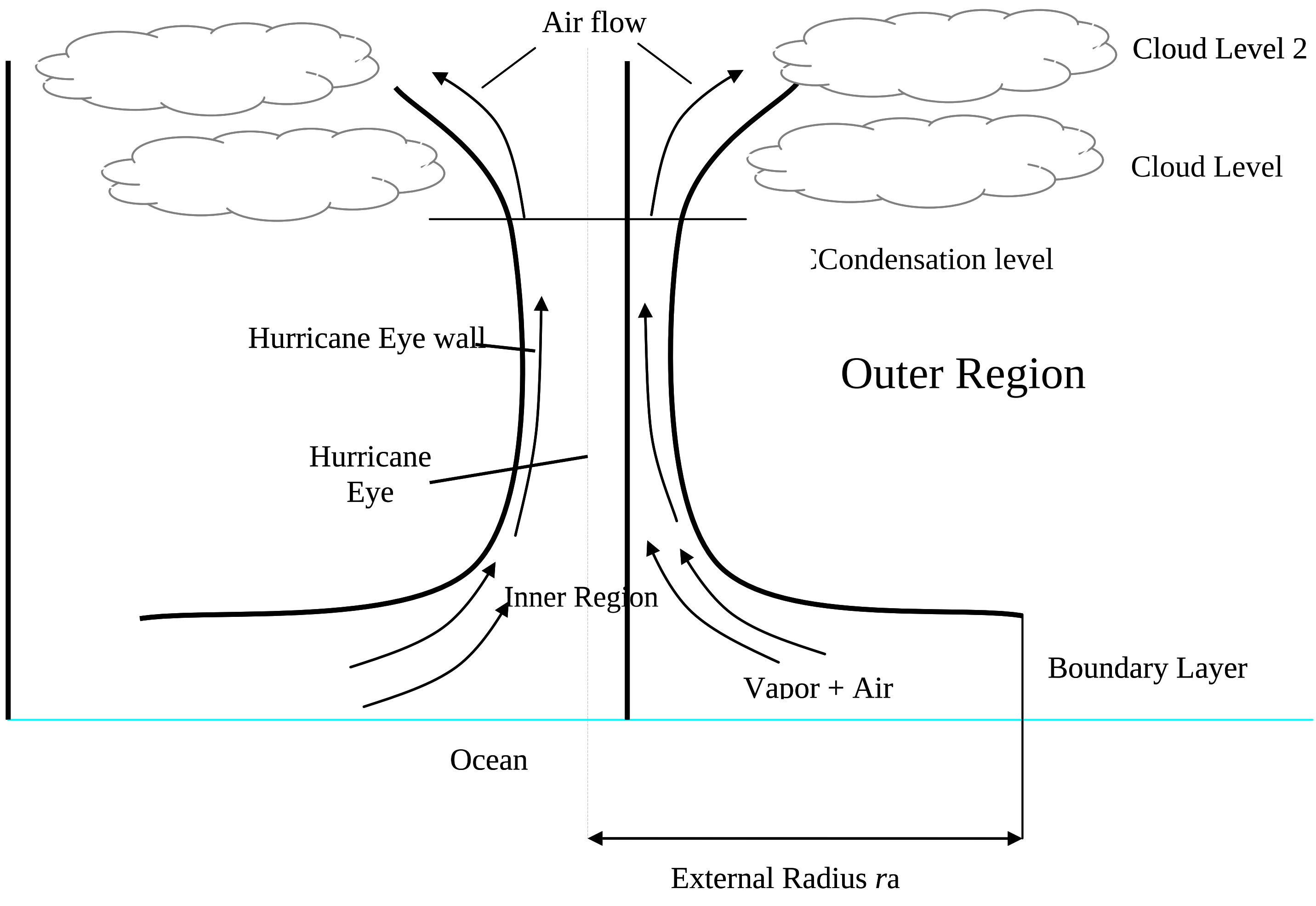
Air flow
Cloud Level 2
Cloud Level
Condensation level
Hurricane Eye wall
Outer Region
Hurricane
Eye
Inner Region
Boundary Layer
Vapor + Air
Ocean
External Radius ra

Figure 1