NUMERICAL SIMULATION OF AERO-OPTICAL FIELDS NEAR AN
OPEN PORT OF AIRBORNE OBSERVATORY

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Abstract. The unsteady turbulent flow over a cavity modelling open port of airborne obser-
vatories is considered. The Reynolds-Averaged Navier-Stokes equations with two-equation
turbulent model are solved using a high-accuracy compact upwind method. To analyse opti-
cal properties of the flow, the locally isotropic turbulence with the Kolmogorov’s spectra is
assumed. The dependence of the optical index of refraction on the parameters is derived. The
results of numerical simulation for various depth, the Mach numbers of flow and geometric of
rear cavity edge are presented. The pulsation regime of the flow generating acoustic fields is
analysed and the optical characteristics of the flow over a cavity are presented.
1 INTRODUCTION

It is well known that the atmosphere influences significantly the resolution properties of optical devices placed at the earth surface. To improve observation conditions, it is possible to place them at airborne platforms with flight altitudes about 10±15 km (fig.1). However, an aerodynamic environment causes optical aberrations, which may lead to degradation of over-all resolution properties of optical systems. When analysing the role of airflow, the zones can be identified. They are “external” zone and thin turbulent boundary layer. When properly designed, airborne platform provides relatively small aberrations in the external zone. It is not the case with boundary or shear layers, which are the main sources of aberrations.

A minimal optical distortion corresponds to boundary layers on smooth surfaces. Hence, cavity with windows protecting an optical system from aerodynamic environment may consider as a good solution of the problem. Unfortunately, for long and medium wavelength infrared region of optical spectra and/or for large diameters of telescope, optical systems need to be placed in the open cavity due to either optical transmission losses and window radiative effect or geometrical considerations. Under the conditions of open cavity, separated shear layer can considerably deteriorate an optical efficiency of the system. It is due to relatively thick turbulent region and unsteady flow causing a powerful acoustic radiation. Thus, the predictions of these effects obtained via numerical simulations may serve as a powerful tool to control them by means, for example, of some aerodynamic devices.

The present paper concerns with numerical simulation of separated turbulent shear layers on the case of open cavities using high-accuracy numerical method and calculations of the relevant air-optical fields.

2 GOVERNING EQUATIONS AND NUMERICAL METHOD

2.1 Basic equations

The problem of unsteady flow of viscous perfect gas near an open cavity is considered using the Reynolds-averaged Navier-Stokes equations with two-equation tur-
bulent Coacley model\(^1\). For a two-dimensional (planar) flow of viscous gas the conservative form of this system written in the Cartesian coordinates (x,y) is

\[
\frac{\partial U(\varphi)}{\partial t} + \frac{\partial F(\varphi)}{\partial x} + \frac{\partial G(\varphi)}{\partial y} = \text{Re}^{-1} \left\{ \frac{\partial}{\partial x} \left[ F_1(\varphi, \varphi_x) + F_2(\varphi, \varphi_y) \right] + \frac{\partial}{\partial y} \left[ G_1(\varphi, \varphi_x) + G_2(\varphi, \varphi_y) \right] \right\},
\]

where

\[
U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \quad F = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ (e + p)u \end{bmatrix}, \quad G = \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ (e + p)v \end{bmatrix}, \quad \varphi = \begin{bmatrix} \hat{n} \\ u \\ v \\ h \end{bmatrix},
\]

\(F_1 = \begin{bmatrix} 0 \\ (4/3) \mu u_x \\ (4/3) \mu u_x + \mu v_x + \mu Pr^{-1} h_i \end{bmatrix}, \quad F_2 = \begin{bmatrix} 0 \\ -(2/3) \mu v_y \\ -(2/3) \mu v_y + \mu vu_y \end{bmatrix},
\]

\(G_1 = \begin{bmatrix} 0 \\ \mu v_x \\ -(2/3) \mu u_x \end{bmatrix}, \quad G_2 = \begin{bmatrix} 0 \\ \mu v_y \\ (4/3) \mu v_y \end{bmatrix},
\]

\[p = \gamma - 1 \rho h, \quad e = \rho \left( \frac{h}{\gamma} + \frac{u^2 + v^2}{2} \right), \quad \mu = \mu_i + \mu_t, \quad \mu Pr^{-1} = \mu_i Pr_i^{-1} + \mu_t Pr_t^{-1}.
\]

Here \(t\) is time, \(\rho\) is density; \(u\) and \(v\) are the velocity components in the \(x\) and \(y\) directions, respectively, \(p\) is pressure, \(h\) is enthalpy, \(e\) is the total energy, \(\gamma\) is the gas ratio of specific heats, \(\mu_i\) and \(\mu_t\) are the molecular and eddy viscosity, respectively, \(Pr\) and \(Pr_t\) are the laminar and turbulent Prandtl numbers, respectively, \(Re\) is the Reynolds number.

The turbulent flow parameters are calculated using the Coacley two-parameter differential model\(^1\). The system of equations of this model in the Cartesian system is:

\[
\frac{\partial U(\bar{\varphi})}{\partial t} + \frac{\partial F(\bar{\varphi})}{\partial x} + \frac{\partial G(\bar{\varphi})}{\partial y} - \mathbf{H}_c = \text{Re}^{-1} \left\{ \frac{\partial}{\partial x} \left[ G_{c1}(\bar{\varphi}, \bar{\varphi}_x) \right] + \frac{\partial}{\partial y} \left[ G_{c2}(\bar{\varphi}, \bar{\varphi}_y) \right] \right\},
\]

\(2.2\)
\[
\begin{align*}
\ddot{\mathbf{o}} &= \begin{bmatrix} q \\ \omega \end{bmatrix}, \\
\mathbf{H}_c &= \begin{bmatrix} h_q \\ \mu_{\omega} \omega \end{bmatrix}, \\
\mathbf{F}_{c1} &= \begin{bmatrix} \mu_q q_x \\ \mu_{\omega} \omega_x \end{bmatrix}, \\
\mathbf{G}_{c2} &= \begin{bmatrix} \mu_q q_y \\ \mu_{\omega} \omega_y \end{bmatrix},
\end{align*}
\]

where \( q = \sqrt{k} \) is the turbulent velocity (\( k \) is the kinetic energy), \( \omega = \sqrt{k/l} \) is the quasi-frequency (\( l \) is the turbulent length scale), \( U_c = \rho \ddot{\mathbf{o}} \), \( \mathbf{F}_c = u \mathbf{U}_c \), \( \mathbf{G}_c = v \mathbf{U}_c \). The components \( h_q \) and \( h_\omega \) of the vector of source terms of the turbulence model are

\[
\begin{align*}
S &= 2u_x^2 + (u_y + v_y)^2 + 2v_y^2 - \frac{2}{3} D^2, \\
D &= u_x + v_y, \\
f &= 1 - \exp\left( -\frac{\alpha \rho q^2}{\mu} Re \right), \\
C_i &= 0.045 + 0.405 f, \\
\mu_i &= C_\mu \rho q^2 f Re \omega^{-1},
\end{align*}
\]

where \( C_\mu = 0.09 \), \( C_\omega = 0.92 \), \( \alpha = 0.0065 \), \( Pr_q = 1 \), \( Pr_\omega = 1.3 \). Using the enthalpy dependence of molecular viscosity given by Sutherland’s formula closes the system.

In our calculations the so-called ‘wall low’ of turbulent boundary layer profile was used. In this concept the nearest points of mesh are located in the logarithmic region and the flow vector is parallel to wall boundary. In that points next equations for \( u, q \) and \( \omega \) are used:

\[
\begin{align*}
u &= u_x \chi^{-1} \ln \left( \frac{9 u_x y}{\mu} \right), \\
\frac{\partial u}{\partial y} &= u_x \chi_y, \\
q &= u_x C_\mu^{1/4}, \\
\omega &= u_x C_\mu^{1/2} / \chi_y, \\
u_t &= \left( \frac{\tau_w}{\rho_w} \right)^{1/2},
\end{align*}
\]

where \( u_x \) is the dynamical speed, \( \tau_w \) is skin friction, \( \rho_w \) is the gas density near the wall, \( \chi \) is the von Karman’s constant and \( y \) is the distance between the grid point and the wall.

### 2.1 Difference algorithm

The algorithm uses the compact upwind third-order differencing formulas (CUD-3) to approximate the hyperbolic parts of systems (2.1) and (2.2) and conventional second-order three-point differences for the viscosity terms. In order to preserve the effectiveness of the algorithm, the system of coordinates is transformed. The region of flow in physical plane \((x,y)\) is projected on to a unit square in the calculation plane.
\((\xi, \eta)\) using mapping in general form. The corresponding Jacobian is \(J^j = x_\xi y_\eta - x_\eta y_\xi\), where \(x_\xi\), \(x_\eta\), \(y_\xi\), and \(y_\eta\) are the metric coefficients.

The system (2.1) written in the coordinates \((\xi, \eta)\) is

\[
\frac{\partial J^{-1}U}{\partial t} + \frac{\partial \mathbf{F}}{\partial \xi} + \frac{\partial \mathbf{G}}{\partial \eta} = \text{Re}^{-1} \left\{ \frac{\partial \left[ \mathbf{F}_1(\varphi, \varphi_\xi) + \mathbf{F}_2(\varphi, \varphi_\eta) \right]}{\partial \xi} + \frac{\partial \left[ \mathbf{G}_1(\varphi, \varphi_\xi) + \mathbf{G}_2(\varphi, \varphi_\eta) \right]}{\partial \eta} \right\},
\]

where \(\mathbf{F} = \mathbf{F}_y - \mathbf{G}_x\), \(\mathbf{G} = \mathbf{G}_x - \mathbf{F}_y\),

\[
\mathbf{F}_1(\varphi, \varphi_\xi) = \mathbf{F}_1 y_\eta^2 - \mathbf{F}_2 y_\xi y_\eta - \mathbf{G}_1 y_\xi y_\eta + \mathbf{G}_2 y_\eta^2, \quad \mathbf{F}_2(\varphi, \varphi_\eta) = -\mathbf{F}_1 y_\eta y_\xi + \mathbf{F}_2 y_\xi y_\eta + \mathbf{G}_1 y_\xi y_\eta - \mathbf{G}_2 y_\xi y_\eta
\]

\[
\mathbf{G}_1(\varphi, \varphi_\xi) = -\mathbf{F}_1 y_\eta y_\xi + \mathbf{F}_2 y_\xi y_\eta + \mathbf{G}_1 y_\xi y_\eta - \mathbf{G}_2 y_\xi y_\eta, \quad \mathbf{G}_2(\varphi, \varphi_\eta) = \mathbf{F}_1 y_\eta^2 - \mathbf{F}_2 y_\xi y_\eta - \mathbf{G}_1 y_\xi y_\eta + \mathbf{G}_2 y_\eta^2
\]

Using grid \(\omega_\xi, \omega_\eta = ih_\xi, jh_\eta, h_\xi, h_\eta = \text{const}\), the approximations of the convective terms of (2.5) may be written as:

\[
L_\phi \phi = B_\xi^{-1} C_\xi \phi + B_\eta^{-1} C_\eta \phi + \mathcal{O}(h_\xi^3 + h_\eta^3),
\]

where

\[
B_\xi f = (A_\xi^5 - 0.25 \Delta_\xi^3 \mathbf{M}_\xi) f, \quad C_\xi f = 0.5 h_\xi^{-1} \left[ \Delta_\xi^5 - \Delta_\xi^4 (T_{0.5}^3 \mathbf{M}_\xi) \Delta_\xi^1 \right] f,
\]

\[
B_\eta f = (A_\eta^5 - 0.25 \Delta_\eta^3 \mathbf{M}_\eta) f, \quad C_\eta f = 0.5 h_\eta^{-1} \left[ \Delta_\eta^5 - \Delta_\eta^4 (T_{0.5}^3 \mathbf{M}_\eta) \Delta_\eta^1 \right] f
\]

are the compact upwind differencing operators which use the following notations:

\[
A_\xi^5 f = \frac{1}{6} (f_{i-1,j} + 4f_{i,j} + f_{i+1,j}), \quad \Delta_\xi^0 f = f_{i+1,j} - f_{i-1,j},
\]

\[
\Delta_\xi^1 f = f_{i,j} - f_{i-1,j}, \quad \Delta_\xi^2 f = f_{i+1,j} - f_{i,j} - \frac{1}{2} (f_{i-1,j} + f_{i,j})
\]

\[
A_\eta^5 f = \frac{1}{6} (f_{i,j-1} + 4f_{i,j} + f_{i,j+1}), \quad \Delta_\eta^0 f = f_{i,j+1} - f_{i,j-1},
\]

\[
\Delta_\eta^1 f = f_{i,j} - f_{i,j-1}, \quad \Delta_\eta^2 f = f_{i,j+1} - f_{i,j} - \frac{1}{2} (f_{i,j+1} + f_{i,j}).
\]

The matrices \(\mathbf{M}_\xi\) and \(\mathbf{M}_\eta\) are determined using the eigenvectors \(S_\xi, S_\eta\) and eigenvalues \(\lambda_\xi, \lambda_\eta\) of the matrices \(\mathbf{N}^{-1}\mathbf{P}\) and \(\mathbf{N}^{-1}\mathbf{Q}\):

\[
\mathbf{M}_\xi = \mathbf{S}_\xi^{-1} \mathbf{N}^{-1} S_\xi, \quad \mathbf{M}_\eta = \mathbf{S}_\eta^{-1} \mathbf{D}_\eta S_\eta^{-1} \mathbf{N}^{-1},
\]

\[
\mathbf{M}_\xi = \mathbf{S}_\eta^{-1} \mathbf{N}^{-1} S_\eta, \quad \mathbf{M}_\eta = \mathbf{S}_\eta^{-1} \mathbf{D}_\eta S_\eta^{-1} \mathbf{N}^{-1}.
\]
where $N = \partial U / \partial \varphi$, $P = \partial F / \partial \varphi$, $Q = \partial G / \partial \varphi$ are Jacobean matrices, $\mathbf{E}_x = \text{diag}\{\lambda_x^l\}$, $\mathbf{E}_y = \text{diag}\{\lambda_y^l\}$, $\mathbf{D}_x = \text{diag}\{\text{sign}\lambda_x^l\}$, $\mathbf{D}_y = \text{diag}\{\text{sign}\lambda_y^l\}$ and $l=1,2,...4$.

The diffusion terms of system (2.3) are approximated in the usual way:

$$L_1 \varphi = (\Lambda_{x} P_1 + \Lambda_{y} P_2 + \Lambda_{\eta} Q_1 + \Lambda_{\eta} Q_2) \varphi + O(h_x^2 / Re + h_\eta^2 / Re),$$

where

$$\Lambda_{x} P_1 \varphi = Re^{-1} h_x^{-2} \Delta_x (T_0 x P_1 ) \Delta_x \varphi, \quad \Lambda_{y} P_2 \varphi = Re^{-1} h_\eta^{-1} h_x^2 \Delta_y (P_2 \Delta_y \varphi),$$

$$\Delta_{x} Q_1 \varphi = Re^{-1} h_x^{-1} h_\eta \Delta_y (T_0 \eta Q_1 ) \Delta_y \varphi, \quad \Delta_{y} Q_2 \varphi = Re^{-1} h_\eta^{-2} \Delta_y (T_0 \xi Q_2 ) \Delta_y \varphi,$$

and the matrices $P_1$, $P_2$, $Q_1$ and $Q_2$ are obtained from the vectors $F_1$, $F_2$, $G_1$ and $G_2$, respectively.

Using operators (2.4) and (2.5) on a grid $\omega_x \times \omega_{\xi, \eta}$, $t_{m}=m\tau$ in the differential analogue of (2.3) can be cast in the form

$$\left( J^{-1} N \right) + B_x^{-1} C_x P + \Lambda_{x} P_1 + B_\eta^{-1} C_\eta Q + \Lambda_{\eta} Q_1 \left( \varphi^{m+1} - \varphi^m \right) = - \left( L_1 \varphi^{m+1} + L_1 \varphi^m \right),$$

(2.6)

the matrices $N$, $P$, $P_1$, $Q$ and $Q_2$ being calculated using flow parameters of the $m$-th time level.

It is convenient to realise the scheme (2.6) by the splitting method$^5$:

$$\left( B_x \frac{J^{-1} N}{\tau} + C_x \varphi \right) = - B_x \left( L_1 \varphi^m + L_1 \varphi^m \right), \quad \left( E + \tau \Lambda_{x} / N^{-1} P_1 \right) \varphi^{1/2} = \varphi^{1/2},$$

$$\left( B_\eta \frac{J^{-1} N}{\tau} + C_\eta \varphi \right) = B_\eta \left( J^{-1} N \right) \varphi^{1/2}, \quad \left( E + \tau \Lambda_{\eta} / N^{-1} Q_2 \right) \varphi^{1/2} = \varphi^{1/2},$$

where $E$ is the identity matrix.

The difference scheme for the turbulent equations (2.2) is constructed in the same manner.

3 DESCRIPTION OF AERO-OPTICAL FIELDS

Air-optical fields are characterised by fluctuations in space and time of the temperature, pressure and other flow variables, which distort phases of passing optical waves. The fluctuation can be induced by two physical phenomena, namely:
• by gas flow turbulence,
• by acoustic processes.

In accordance with the above classification, one may introduce some reference steady state (or quasi steady state) field and two components of fluctuations. The first one is the turbulent component described stochastically while the second one is deterministic acoustic component.

3.1 Turbulent component

One of the ways to describe turbulent fields is to use the hypothesis of locally uniform and isotropic model with Kolmogorov's spectra of pulsations\(^6\). In the context of the optical applications, it is sufficient to know the distribution of maximal (in certain cases, minimal) pulsation scale \(l_e\) (or \(l_i\)) respectively and distribution of the so-called structural characteristic of the refraction index field. Basing on the Kolmogorov's theory, the latter is defined by \(Cn^2=[7.92\cdot10^5k(\lambda)p/T^2]^{2}C_{T}^2\), where \(C_{T}^2=\alpha^2l_{e}^{4/3}Pr(\text{grad}T)^2\) is the parameter of the temperature field, \(T\) is temperature, \(\lambda\) is the wavelength, \(k(\lambda)\) is relative index of the refraction, \(\alpha^2=1/3\). The turbulent scale \(l_e\) can be defined as \(l_e=\beta q/\omega\), where \(\beta=1\).

3.2 Acoustic component

When using open cavities for placing optical systems on airborne platforms, one encounters with degradation of optical performance due to the so-called cavity resonance. This is usually manifested by single-frequency pressure fluctuations, which is both experimental and numerical\(^7\) evidence.

For a cavity longitude scale \(L=1\text{ m}\), the pulsation frequency may be about \(10\div100\text{Hz}\) while sound-pressure levels may reach \(100\div150\text{Db}\) for the Mach numbers \(M_1=0.6\div0.8\). The effect is due to the instability of a shear layer formed at the leading edge of the cavity. This kind of instability is dated back to the Reyleigh works.

The calculations for cavity flows show that the spectrum of acoustic fluctuations is relatively narrow and flow varies in space (see fig.2). There-
fore, one may consider the mean and acoustic components at any aero-optical variable \( f(t,r) \) as a harmonic function

\[
f = f_0(r) + A(r) \cdot \sin[\omega t + \varphi(r)]
\]  

(3.1)

where \( \omega = \text{const} \) is the frequency while \( f_0 \), \( A \) and \( \varphi \) are spatial distributions of the mean value of \( f \), its amplitude and phase respectively. To obtain \( f_0(r) \), \( A(r) \) and \( \varphi(r) \), we use the following averaging of calculated unsteady fields:

\[
<f(t,r)> = \lim_{t \to t_0} \frac{1}{t-t_0} \int_0^t f(t',r) \, dt'
\]  

(3.2)

One can see that

\[
f_0(r) = <f(t,r)>, \quad A^2(r) = \frac{2}{\int_0^t [f(t,r)-f_0(r)]^2 dt},
\]

\[
cos[\varphi(r)] = \frac{2}{A(r)A(r_0)} <[f(t,r)-f_0(r)][f(t,r_0)-f_0(r_0)]>
\]

where \( r_0 \) is a point where the fluctuation phase \( \varphi \) is zero.

As a measure of optical distortion, one can use the eiconal perturbation due to turbulence processes:

\[
\delta L_t = \left[ \int_{\delta} C_n^{2/3} dy \right]^{1/2}
\]  

(3.3)

where the integration is performed over the high of boundary layer.

4 AERO-OPTICAL FIELDS NEAR AIRBORNE-PLATFORM CAVITY

To estimate parameters of fields generated by airborne-platform cavity, calculations were carried out for 2D case using the above-described methodology. The cavity length was assumed to be \( L=5\text{m} \) and the base depth \( 3\text{m} \). The Mach number interval was changed from 0.7 to 1.1 and altitude of flight from 10 to 15 km. The Reynolds number per 1m was assumed to be \( 5\cdot10^6 \). The boundary thickness was 0.1 m.

The calculations showed the well-known phenomena of a shear layer separation from the leading edge of the cavity. The shear layer is essentially unsteady deflecting into the cavity thus increasing the cavity pressure. In turn the increased pressure forces the shear layer outside the cavity thus producing its oscillations. The oscillations with corresponded pressure pulsation were fond to be quasi-periodic (as shown in fig.2). They generate the above discussed acoustic component, which can be estimated quantitatively according to Subsection 3.2. Following the methodology briefly outlined in Subsection 3.1, the \( C_n \) and \( \delta L_t \) parameters other resulting aero-optical fields can be calculated using \( q \) and \( \varphi \) parameters of turbulence concentrated in the shear layer. It should be noted that the unsteady shear layer separation is quite com-
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The complicated process characterising by strong coupling of the external flow outside the cavity and the cavity flow.

The eiconal perturbation along the cavity outer boundary is shown in fig.3. The perturbation arises due to turbulent flow pulsation (see formula (3.3)). The calculations show that for the cavity depth $h=3m$, intense acoustic oscillations with frequency $50Hz$ are generated. (see fig.4). The oscillations and non-uniform distributions of the pressure and temperature can additionally disturb phases of optical waves. As a measure of such distortion, one can use

the following parameter of the eiconal perturbation:

$$\delta L_n = \int_{(s)} n \Delta dy$$

where $\Delta n$ is the perturbation of the refraction index $n$ while integration is performed over height of the shear layer above the telescopes apertures.

The distribution of $\delta L_n$ in the cavity depends on mean and acoustic components of pressure and temperature. In fig.5 the distribution of $\delta L_n$ along the cavity outer boundary are shown for three successive time moments. Our calculations have shown considerable dependence of the acoustic amplitudes on the cavity geometry. For example, the increase of cavity depth from 3 to 5m leads to decrease the amplitudes up to $25 \div 30$ times of magnitude (see fig.6). Another way to improve optical properties of a shear layer is to change the geometry of its trailing edge. Fig.7 shows that in case B maximal values of $C_n$ are concentrated in thinner layer near the outer boundary. The decrease of the level of the refraction index dispersion

Fig.3. Eiconal perturbation in the shear layer. Bold lines correspond to telescope apertures.

Fig.4. Contours of normalised amplitude of pressure pulsation and displacement of phase oscillations for cavity with depth $h=3m$. Flight height and Mach number are 10 km and 0.8 respectively.
in the forward portion of the shear layer due to rounded trailing edge is shown in fig. 8.

In conclusion, numerical simulation of turbulent aero-optical fields may provide significant information for engineering predictions of performance of optical systems placed at airborne platforms. Moreover to certain extent, by varying cavity geometry one can control the relevant separated flows thus optimising the resolution properties of optical devises.

Fig. 6. Contours of normalised amplitudes of pressure pulsation for cavities with different depths. Flight height and Mach number are 10 km and 0.8 respectively.

Fig. 5. Eiconal perturbation in the shear layer due to non-uniform (in space and time) density and pressure fields for cavity with depth $h=3\text{m}$. Flight height and Mach number are 10 km and 0.8 respectively. Curves 1, 2 and 3 correspond to time moments differing by the diameter of the acoustic pulsation period.
Fig. 7. Contours of phase variance in the shear layer. Flight height and Mach number are 10 km and 0.8 respectively.

Fig. 8. Contours of dispersion of the refraction index due to acoustic oscillations.

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