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# Geometric evolution of the Reynolds stress tensor in three-dimensional turbulence

Sergey Gavriluk <sup>\*</sup> and Henri Gouin <sup>†</sup>

## Abstract

The dynamics of the Reynolds stress tensor is given by an evolution equation coupling geometrical effects and turbulent source terms. The effects of the mean flow geometry are shown up when the source terms are neglected. In this case, the Reynolds stress tensor is expressed as the sum of three tensor products of vector fields only associated with the mean flow. The vector fields are governed by differential equations similar to a distorted gyroscopic equation. Along the trajectories of mean flow, the fluctuations of velocity are determined by a differential equation whose coefficients only depend on the eigenvalues of the mean rate of deformation tensor.

## 1 Introduction

The governing equations of barotropic turbulent compressible fluids are (see, for example [1], [2]):

$$\left\{ \begin{array}{l} \langle \rho \rangle_t + (\langle \rho \rangle U_i)_{,i} = 0, \\ (\langle \rho \rangle U_i)_t + (\langle \rho \rangle U_i U_j + \langle p \rangle \delta_{ij} + \langle \rho u_i u_j \rangle)_{,j} = 0, \\ \langle \rho u_i u_j \rangle_t + (\langle \rho u_i u_j \rangle U_k)_{,k} + \langle \rho u_i u_j \rangle U_{j,k} + \langle \rho u_i u_j \rangle U_{i,k} = S_{ij}. \end{array} \right. \quad (1)$$

Here “brackets” mean the averaging, “coma” means the derivation with respect to the Eulerian coordinates  $\mathbf{x} = \{x_i\}$ ,  $i \in \{1, 2, 3\}$ ,  $\rho$  is the fluid density,  $\mathbf{U} = \{U_i\}$ ,  $i \in \{1, 2, 3\}$  is the mass average velocity,  $p$  is the pressure,  $\mathbf{u} = \{u_i\}$ ,  $i \in \{1, 2, 3\}$  is the velocity fluctuation verifying  $\langle \rho \mathbf{u} \rangle = 0$ . Repeated indices mean summation. The term  $\mathbf{S} = \{S_{ij}\}$  represents turbulent sources. We introduce the Reynolds stress tensor:

$$\mathbf{R} = \langle \rho \mathbf{u} \otimes \mathbf{u} \rangle, \quad (R_{ij} = \langle \rho u_i u_j \rangle).$$

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The system (1) can also be rewritten in the tensorial form:

$$\left\{ \begin{array}{l} \frac{\partial \langle \rho \rangle}{\partial t} + \operatorname{div} (\langle \rho \rangle \mathbf{U}) = 0, \\ \langle \rho \rangle \frac{d\mathbf{U}}{dt} + \nabla \langle p \rangle + \operatorname{div} \mathbf{R} = 0, \\ \frac{d\mathbf{R}}{dt} + \mathbf{R} \operatorname{div} \mathbf{U} + \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{R} + \mathbf{R} \left( \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \right)^T = \mathbf{S}, \end{array} \right. \quad (2)$$

where  $d/dt$  means the material derivative with respect to the mean motion:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{U}^T \nabla .$$

The superscript "  $T$  " means the transposition. Using the mass conservation law, the equation for the volumic Reynolds tensor  $\mathbf{R}$  can be rewritten as the equation for the specific (or per unit mass) Reynolds tensor:

$$\frac{d\mathbf{P}}{dt} + \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{P} + \mathbf{P} \left( \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \right)^T = \frac{\mathbf{S}}{\langle \rho \rangle}, \quad (3)$$

where

$$\mathbf{P} = \frac{\mathbf{R}}{\langle \rho \rangle}.$$

The aim of this note is to understand the structure of homogeneous Reynolds equation (3) corresponding to  $\mathbf{S} = \mathbf{0}$ . The reason is twofold:

- first, in the numerical study of compressible turbulent flows, this is a natural step in applying the splitting-up technique (see for example [3]),
- second, the system (2) also appears as an exact asymptotic model of weakly shearing flows of long waves over a flat bottom [4]:

$$\left\{ \begin{array}{l} \frac{\partial h}{\partial t} + \operatorname{div} (h \mathbf{U}) = 0, \\ h \frac{d\mathbf{U}}{dt} + \nabla \left( \frac{gh^2}{2} \right) + \operatorname{div} \mathbf{R} = 0, \\ \frac{d\mathbf{R}}{dt} + \mathbf{R} \operatorname{div} \mathbf{U} + \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{R} + \mathbf{R} \left( \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \right)^T = 0. \end{array} \right. \quad (4)$$

In Eq. (4),  $h$  is the fluid depth, the average pressure is given by  $\langle p \rangle = gh^2/2$ ,  $g$  is the gravity acceleration, and

$$\mathbf{R} = \int_0^h (\tilde{\mathbf{U}} - \mathbf{U}) \otimes (\tilde{\mathbf{U}} - \mathbf{U}) dz, \quad h\mathbf{U} = \int_0^h \tilde{\mathbf{U}} dz,$$

where  $\tilde{\mathbf{U}}$  is an instantaneous velocity. Equations are written for three-dimensional long waves and the production term is zero in the limit of weakly shearing flows.

Also, Eqs. (4) are hyperbolic. Finally, we will focus on the equation of the Reynolds tensor per unit mass:

$$\frac{d\mathbf{P}}{dt} + \frac{\partial\mathbf{U}}{\partial\mathbf{x}} \mathbf{P} + \mathbf{P} \left( \frac{\partial\mathbf{U}}{\partial\mathbf{x}} \right)^T = 0. \quad (5)$$

The particular case  $\text{rot } \mathbf{U} = 0$  was investigated in [5]. In such a case  $(\partial\mathbf{U}/\partial\mathbf{x})^T = \partial\mathbf{U}/\partial\mathbf{x}$  and Eq. (5) corresponds to a two-covariant tensor convected by the mean flow. This means that  $\mathbf{P}$  has a zero Lie derivative  $d_L$  with respect to the velocity field  $\mathbf{U}$  and the tensor  $\mathbf{P}_0$ , image of  $\mathbf{P}$  in Lagrange coordinates  $(t, \mathbf{X})$ , only depends on  $\mathbf{X} = \{X_i\}$ ,  $i \in \{1, 2, 3\}$ :

$$d_L \mathbf{P} \equiv \frac{d\mathbf{P}}{dt} + \frac{\partial\mathbf{U}}{\partial\mathbf{x}} \mathbf{P} + \mathbf{P} \frac{\partial\mathbf{U}}{\partial\mathbf{x}} = 0, \quad \mathbf{P} = (F^T)^{-1} \mathbf{P}_0(\mathbf{X}) F^{-1},$$

where  $F = \partial\mathbf{x}/\partial\mathbf{X}$  is the deformation gradient of the mean motion [6].

The aim of the paper is the study of the homogeneous Reynolds equation (5) in *the case*  $\text{rot } \mathbf{U} \neq 0$ .

## 2 Geometrical properties of the Reynolds tensor evolution

The Reynolds stress tensor  $\mathbf{R}$  (and, consequently  $\mathbf{P}$ ) is symmetric and semi-positive definite. The tensor  $\mathbf{P}$  can be written in a local basis of orthonormal eigenvectors in the form:

$$\mathbf{P} = \sum_{\alpha=1}^3 \lambda_\alpha^2 \mathbf{e}_\alpha \otimes \mathbf{e}_\alpha \equiv \sum_{\alpha=1}^3 \lambda_\alpha^2 \mathbf{e}_\alpha \mathbf{e}_\alpha^T.$$

The eigenvalues  $\lambda_\alpha^2$ ,  $\alpha \in \{1, 2, 3\}$  are non-negative; the case  $\lambda_\alpha^2 > 0$  is a generic one. For the two-dimensional case,  $\lambda_3^2 \equiv 0$ . Let us denote:

$$\mathbf{a}_\alpha = \lambda_\alpha \mathbf{e}_\alpha, \quad (\lambda_\alpha > 0) \quad \alpha \in \{1, 2, 3\}. \quad (6)$$

Then,

$$\mathbf{P} = \sum_{\alpha=1}^3 \mathbf{a}_\alpha \otimes \mathbf{a}_\alpha \equiv \sum_{\alpha=1}^3 \mathbf{a}_\alpha \mathbf{a}_\alpha^T. \quad (7)$$

From Eq. (7), we deduce:

$$\frac{d\mathbf{P}}{dt} = \sum_{\alpha=1}^3 \frac{d\mathbf{a}_\alpha}{dt} \mathbf{a}_\alpha^T + \mathbf{a}_\alpha \left( \frac{d\mathbf{a}_\alpha}{dt} \right)^T. \quad (8)$$

By using Eq. (8), Eq. (5) can be written:

$$\sum_{\alpha=1}^3 \left( \frac{d\mathbf{a}_\alpha}{dt} + \frac{\partial\mathbf{U}}{\partial\mathbf{x}} \mathbf{a}_\alpha \right) \mathbf{a}_\alpha^T + \left[ \left( \frac{d\mathbf{a}_\alpha}{dt} + \frac{\partial\mathbf{U}}{\partial\mathbf{x}} \mathbf{a}_\alpha \right) \mathbf{a}_\alpha^T \right]^T = 0. \quad (9)$$

The vector  $d\mathbf{a}_\alpha/dt + (\partial\mathbf{U}/\partial\mathbf{x})\mathbf{a}_\alpha$  can be developed in the local basis  $\{\mathbf{a}_\alpha\}$ ,  $\alpha \in \{1, 2, 3\}$  of eigenvectors; one obtains:

$$\frac{d\mathbf{a}_\alpha}{dt} + \frac{\partial\mathbf{U}}{\partial\mathbf{x}}\mathbf{a}_\alpha = \sum_{\beta=1}^3 A_{\beta\alpha}\mathbf{a}_\beta, \quad \alpha \in \{1, 2, 3\} \quad (10)$$

where  $A_{\beta\alpha}$ ,  $(\alpha, \beta \in \{1, 2, 3\})$  are the scalar components to be determined. By using Eq. (10), Eq. (9) leads to:

$$\sum_{\alpha=1}^3 A_{\alpha\alpha}\mathbf{g}_{\alpha\alpha} + \sum_{\alpha \neq \beta=1}^3 (A_{\alpha\beta} + A_{\beta\alpha})\mathbf{g}_{\alpha\beta} = 0,$$

where  $\mathbf{g}_{\alpha\alpha} = 2\mathbf{a}_\alpha\mathbf{a}_\alpha^T$  and  $\mathbf{g}_{\alpha\beta} = \mathbf{g}_{\beta\alpha} = \mathbf{a}_\alpha\mathbf{a}_\beta^T + \mathbf{a}_\beta\mathbf{a}_\alpha^T$ ,  $(\alpha, \beta \in \{1, 2, 3\})$ , are six independent symmetric tensors. Consequently,

$$A_{\alpha\alpha} = 0 \quad \text{and} \quad A_{\alpha\beta} + A_{\beta\alpha} = 0, \quad \alpha, \beta \in \{1, 2, 3\}.$$

Equation (9) is equivalent to:

$$\frac{d\mathbf{a}_\alpha}{dt} + \frac{\partial\mathbf{U}}{\partial\mathbf{x}}\mathbf{a}_\alpha = \pi \times \mathbf{a}_\alpha \quad \text{with} \quad \pi = A_{32}\mathbf{a}_1 + A_{13}\mathbf{a}_2 + A_{21}\mathbf{a}_3, \quad \alpha \in \{1, 2, 3\}. \quad (11)$$

The vectors  $\mathbf{a}_\alpha$ ,  $\alpha \in \{1, 2, 3\}$  are orthogonal,  $\mathbf{a}_\alpha^T\mathbf{a}_\beta = 0$ ,  $(\alpha \neq \beta)$ ; if we assume the orthogonality at initial instant, this is equivalent to:

$$\mathbf{a}_\alpha^T \frac{d\mathbf{a}_\beta}{dt} + \mathbf{a}_\beta^T \frac{d\mathbf{a}_\alpha}{dt} = 0. \quad (12)$$

So, Eqs. (11) - (12) yield:

$$\forall \alpha \neq \beta \in \{1, 2, 3\}, \quad \mathbf{a}_\alpha^T \left( \pi \times \mathbf{a}_\beta - \frac{\partial\mathbf{U}}{\partial\mathbf{x}}\mathbf{a}_\beta \right) + \mathbf{a}_\beta^T \left( \pi \times \mathbf{a}_\alpha - \frac{\partial\mathbf{U}}{\partial\mathbf{x}}\mathbf{a}_\alpha \right) = 0.$$

From definition (6), we obtain:

$$\mathbf{e}_\alpha^T \mathbf{D} \mathbf{e}_\beta = 0 \quad (\alpha \neq \beta),$$

where

$$\mathbf{D} = \frac{1}{2} \left( \frac{\partial\mathbf{U}}{\partial\mathbf{x}} + \left( \frac{\partial\mathbf{U}}{\partial\mathbf{x}} \right)^T \right)$$

is the rate of deformation tensor corresponding to the mean flow. We immediately deduce the theorem:

**Theorem 1.** *The orthonormal eigenvectors  $\mathbf{e}_\alpha$ ,  $\alpha \in \{1, 2, 3\}$  of the Reynolds stress tensor  $\mathbf{P}$  are also the orthonormal eigenvectors of the mean rate of deformation tensor  $\mathbf{D}$ .*

The eigenvalues of  $\mathbf{D}$  will be denoted by  $\mu_\alpha$ :  $\mathbf{D}\mathbf{e}_\alpha = \mu_\alpha\mathbf{e}_\alpha$ ,  $\alpha \in \{1, 2, 3\}$ .

### 3 Transport of the Reynolds stress tensor

By taking Eq. (6) into account in Eq. (11), we obtain:

$$\lambda_\alpha \frac{d\mathbf{e}_\alpha}{dt} + \frac{d\lambda_\alpha}{dt} \mathbf{e}_\alpha + \lambda_\alpha \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{e}_\alpha - \lambda_\alpha \boldsymbol{\pi} \times \mathbf{e}_\alpha = 0, \quad \alpha \in \{1, 2, 3\}. \quad (13)$$

Equation (13) is equivalent to the system of equations obtained by projections on  $\mathbf{e}_\alpha$  and orthogonally to  $\mathbf{e}_\alpha$  respectively:

$$\left\{ \begin{array}{l} \frac{d\lambda_\alpha}{dt} + (\mathbf{e}_\alpha^T \mathbf{D} \mathbf{e}_\alpha) \lambda_\alpha = 0, \\ \frac{d\mathbf{e}_\alpha}{dt} + (\mathbf{I} - \mathbf{e}_\alpha \mathbf{e}_\alpha^T) \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{e}_\alpha - \boldsymbol{\pi} \times \mathbf{e}_\alpha = 0, \end{array} \right. \quad \alpha \in \{1, 2, 3\} \quad (14)$$

where  $\mathbf{I}$  is the identity tensor. Equation (14<sub>1</sub>) is equivalent to:

$$\frac{d\lambda_\alpha}{dt} + \mu_\alpha \lambda_\alpha = 0.$$

Due to the fact that:

$$\begin{aligned} (1 - \mathbf{e}_\alpha \mathbf{e}_\alpha^T) \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{e}_\alpha &= \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{e}_\alpha - \mathbf{e}_\alpha \left( \mathbf{e}_\alpha^T \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{e}_\alpha \right) = \\ &= \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{e}_\alpha - \mu_\alpha \mathbf{e}_\alpha = \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \mathbf{e}_\alpha - \mathbf{D} \mathbf{e}_\alpha = \frac{1}{2} \text{rot } \mathbf{U} \times \mathbf{e}_\alpha, \end{aligned}$$

we obtain

$$\frac{d\mathbf{e}_\alpha}{dt} - \boldsymbol{\Pi} \times \mathbf{e}_\alpha = 0,$$

where  $\boldsymbol{\Pi} = \boldsymbol{\pi} - \frac{1}{2} \text{rot } \mathbf{U}$  is a vector of rotation associated with the mean field motion. Let us note that:

$$\boldsymbol{\Pi} = \frac{1}{2} \sum_{\alpha=1}^3 \mathbf{e}_\alpha \times \frac{d\mathbf{e}_\alpha}{dt}$$

and consequently can be directly calculated by using the direct orthonormal system of the eigenvectors of the mean rate of deformation tensor  $\mathbf{D}$ . Finally, the property follows:

**Theorem 2.** *In the homogeneous case, the Reynolds tensor can be written in the form*

$$\mathbf{R} = \langle \rho \rangle \sum_{\alpha=1}^3 \lambda_\alpha^2 \mathbf{e}_\alpha \otimes \mathbf{e}_\alpha,$$

where  $\{\mathbf{e}_\alpha\}$ ,  $\alpha \in \{1, 2, 3\}$  are the orthonormal eigenvectors of the mean rate of deformation tensor  $\mathbf{D} = \frac{1}{2} \left( \frac{\partial \mathbf{U}}{\partial \mathbf{x}} + \left( \frac{\partial \mathbf{U}}{\partial \mathbf{x}} \right)^T \right)$ . The eigenvectors  $\mathbf{e}_\alpha$  and the

eigenvalues  $\lambda_\alpha^2$  verify the equations:

$$\left\{ \begin{array}{l} \frac{d\mathbf{e}_\alpha}{dt} = \mathbf{\Pi} \times \mathbf{e}_\alpha, \\ \frac{d(\text{Ln } \lambda_\alpha^2)}{dt} = -2 \mu_\alpha, \end{array} \right. \quad \alpha \in \{1, 2, 3\} \quad (15)$$

where

$$\mu_\alpha = \mathbf{e}_\alpha^T \mathbf{D} \mathbf{e}_\alpha, \quad \mathbf{\Pi} = \frac{1}{2} \sum_{\alpha=1}^3 \mathbf{e}_\alpha \times \frac{d\mathbf{e}_\alpha}{dt}.$$

Equation (15<sub>1</sub>) is similar to the equations of a rigid body [7]. The vectors  $\mathbf{e}_\alpha$  form a natural moving frame  $G = \{\mathbf{e}_\alpha\}_{\alpha=1}^3$  only calculated with the mean motion. The eigenvalues  $\lambda_\alpha^2$  of the Reynolds tensor are determined by the key evolution equation (15<sub>2</sub>).

**Remark:** Theorems 1 and 2 prove there exists a relation between  $\mathbf{P}$  and  $\mathbf{D}$  in the form:

$$\mathbf{P} = a\mathbf{I} + b\mathbf{D} + c\mathbf{D}^2 \quad (16)$$

Equation (16) is equivalent to the system of three linear equations in the form

$$\lambda_\alpha^2 = a + b\mu_\alpha + c\mu_\alpha^2, \quad \alpha \in \{1, 2, 3\}, \quad (17)$$

with respect to  $a, b, c$ . Here,  $\lambda_\alpha$  are determined by Eq. (15<sub>2</sub>). If  $\mu_\alpha$  are different, we obtain a unique solution of system (17). Equation (16) is often proposed in the literature as a phenomenological constitutive law which is similar to the Stokes hypothesis for viscous fluids (see for example [8]). In the homogeneous cases, we have proved that Eq. (16) is not a constitutive law but one of the basic consequences of the geometrical properties of the Reynolds stress tensor.

Due to Eq. (2<sub>2</sub>) and Eq. (15<sub>2</sub>), we obtain:

$$\frac{d}{dt} \left( \langle \rho \rangle^{-2} \prod_{\alpha=1}^3 \lambda_\alpha^2 \right) = 0.$$

Consequently, system (15) admits a scalar invariant along the trajectories of mean flow. This invariant was earlier obtained in [5] in a different form.

Let us introduce the turbulent specific energy:

$$e_T = \frac{1}{2} \text{tr } \mathbf{P} = \frac{1}{2} \sum_{\alpha=1}^3 \lambda_\alpha^2.$$

In the incompressible (isochoric) case, we have  $d\langle \rho \rangle/dt = 0$ ; the turbulent energy is minimal in the isotropic case when the three eigenvalues  $\lambda_\alpha^2$  are equal:  $\lambda_1^2 = \lambda_2^2 = \lambda_3^2 = \lambda^2$ .

In the compressible isotropic case  $e_T = \langle \rho \rangle^{2/3} \kappa$ ,  $\kappa = 3\lambda^2/(2\langle \rho \rangle^{2/3})$ , and  $\kappa$  is a classical invariant of isotropic turbulence. In presence of shock waves the

quantity  $\langle \rho \rangle^{-2} \prod_{\alpha=1}^3 \lambda_{\alpha}^2$  is not conserved through shocks; it increases like the classical entropy in compressible fluid dynamics. The estimation of the jump of turbulence entropy in isotropic case was given in [9].

In general case, the energy conservation law for homogeneous system (2) can be written in the form:

$$\frac{\partial}{\partial t} \left( \langle \rho \rangle \left( \frac{1}{2} |\mathbf{U}|^2 + e_i + e_T \right) \right) + \operatorname{div} \left( \langle \rho \rangle \mathbf{U} \left( \frac{1}{2} |\mathbf{U}|^2 + e_i \right) + (\langle p \rangle \mathbf{I} + \mathbf{R}) \mathbf{U} \right) = 0,$$

where the internal specific energy  $e_i$  is defined by

$$de_i = -\langle p \rangle d \left( \frac{1}{\langle \rho \rangle} \right)$$

and the mean pressure  $\langle p \rangle$  is supposed to be a given function of  $\langle \rho \rangle$ . Indeed,

$$\begin{aligned} \frac{\partial}{\partial t} \left( \langle \rho \rangle \left( \frac{1}{2} |\mathbf{U}|^2 + e_i + e_T \right) \right) + \operatorname{div} \left( \langle \rho \rangle \mathbf{U} \left( \frac{1}{2} |\mathbf{U}|^2 + e_i \right) + (\langle p \rangle \mathbf{I} + \mathbf{R}) \mathbf{U} \right) = \\ \langle \rho \rangle \frac{de_T}{dt} + \operatorname{tr}(\mathbf{R} \mathbf{D}) = \\ \frac{\langle \rho \rangle}{2} \frac{d}{dt} \left( \sum_{\alpha=1}^3 \lambda_{\alpha}^2 \right) + \langle \rho \rangle \operatorname{tr} \left( \sum_{\alpha=1}^3 \lambda_{\alpha}^2 \mu_{\alpha} \right) = 0. \end{aligned}$$

## 4 Conclusion

The equations of fluid turbulent motions take three equations into account: the equation of the mass balance (1<sub>1</sub>), the balance equation of the average momentum (1<sub>2</sub>), and the Reynolds stress tensor equation of evolution (1<sub>3</sub>); this last equation has been the object of our study. If the turbulent sources are neglected, the turbulent fluid motion is a superposition of the mean motion and turbulent fluctuations. The eigenvectors of the Reynolds tensor carry the fluctuations associated with the deformation. The amplitude of turbulent deformations is defined by the eigenvalues of the Reynolds stress tensor. Locally, the equations for the directions of turbulent fluctuations describe a small solid whose rotation is given by a gyroscopic type equation (Equation (15<sub>1</sub>)). The amplitude evolution of turbulent deformations is determined by the eigenvalues  $\mu_{\alpha}$  of the rate of deformation tensor  $\mathbf{D}$ . The turbulence increases with the time when  $\mu_{\alpha} < 0$ , and decreases when  $\mu_{\alpha} > 0$ . In the particular case of incompressible fluid motions we have  $\operatorname{tr} \mathbf{D} = 0$ , and hence there always exists a direction in which the turbulence is increasing while in other directions it is decreasing. These mathematical deductions are confirmed by experiments [10].

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