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TEMPORAL TRACKING OF THE INTENSE VORTICITY STRUCTURES IN ISOTROPIC TURBULENCE: LIFETIME DYNAMICS

Lucas S. Fonseca,
Department of Mechanical Engineering
Instituto Superior Técnico,
University of Lisbon
Av. Rovisco Pais, 1049-001 Lisboa,
Portugal
lucas.fonseca@tecnico.ulisboa.pt

Afonso A. Ghira
Department of Mechanical Engineering
Instituto Superior Técnico,
University of Lisbon
Av. Rovisco Pais, 1049-001 Lisboa,
Portugal
afonso.ghira@tecnico.ulisboa.pt

Carlos B. da Silva
Department of Mechanical Engineering
Instituto Superior Técnico
University of Lisbon
Av. Rovisco Pais, 1049-001 Lisboa,
Portugal
carlos.silva@tecnico.ulisboa.pt

ABSTRACT

A temporal tracking algorithm is used to follow in time millions of individual intense vorticity structures (IVS or 'worms') in homogeneous isotropic turbulence (HIT), from their 'births' to their 'deaths', and to store the instantaneous axial profiles of several of their characteristics, e.g., radius and axial vorticity profiles, as well as several turbulent variables acting at their axis, e.g. enstrophy production. The results of the analysis of lifetime data from millions of 'worms', with Reynolds numbers up to $Re_\lambda = 190$, show that the local worm characteristics do not affect their total life time, and suggest that their 'deaths' i.e. the break down or final dissipation of these structures, is caused by external flow events, e.g., approaching nearby vortices, and not by instabilities observed at the axis of the structures.

INTRODUCTION

The intense vorticity structures (IVS) or worms are the smallest-scale eddies that can be found in a turbulent flow, and have often been defined as the structures having a vorticity magnitude that is above a certain (high) threshold, occupying 1% of the flow domain (Jiménez et al. (1993) and Jiménez and Wray (1998)). Their diameter is typically equal to 10 Kolmogorov length scales η, and their tangential velocity is tipically equal to the root-mean-square velocity, u'. Their length scale scales with the Kolmogorov length scale l_{ivs} and its mean value is typically equal to the 55η (Ghira, Elsinga & da Silva 2022).

Recently, a new temporal vortex tracking algorithm was developed which allowed to efficiently track down in time millions of IVS. This then permitted to directly measure the life time of each individual IVS. From the survival function, i.e. the probability of an IVS being 'alive' for a certain time after being 'born', it was possible to compute the mean lifetime of the IVS in HIT. The results shown that very long living IVS, with a life time comparable to the integral time scale, are relatively rare, and that the mean life time of the IVS scales with the rotation time scale, $\tau_{ivs} \sim \tau_{rot}$, where $\tau_{rot} \sim \eta/u'$ (Ghira, Elsinga & da Silva 2025).

The goal of this work is to investigate the dynamics of these structures from their 'births' to their 'deaths', and for this purpose we stored axial data for millions of worms along their entire life, including axial profiles of vortex radius, tangential velocity, vorticity magnitude, and also, enstrophy variation, enstrophy production, enstrophy diffusion and enstrophy dissipation.

DIRECT NUMERICAL SIMULATIONS OF HIT

A total of 4 direct numerical simulations (DNS) of statistically stationary (forced) homogeneous isotropic turbulence (HIT) were carried out. The DNS employ the same code described in Ghira, Elsinga & da Silva 2022 which is an in-house Navier-Stokes solver using classical pseudo-spectral methods for spatial discretization and a 3-stage, 3^{rd}-order Runge-Kutta scheme for temporal advancement. The simulations are carried out in a triple periodic domain of sizes $2\pi \times 2\pi \times 2\pi$ using N^3 collocation points.

The number of collocation points in the simulations varies between $128^3 \leq N^3 \leq 1024^3$ and the Reynolds number between $54 \leq Re_\lambda \leq 239$, and the resolution is always kept at $k_{max}\eta = 2.0$. Statistical stationarity is obtained by imposing a power input through the imposed forcing f_i which balances the viscous dissipation rate, $P = \varepsilon$, where $P = \overline{f_i u_i}$ is the power of the input forcing and $\varepsilon = 2\nu\overline{s_{ij}s_{ij}}$, is the viscous dissipation rate, and $s_{ij} = (\partial u_i/\partial x_j + \partial u_j/\partial x_i)/2$ is the rate-of-strain tensor.

The forcing scheme implemented here is described in Alvelius 1999 and all the simulations use the same power of

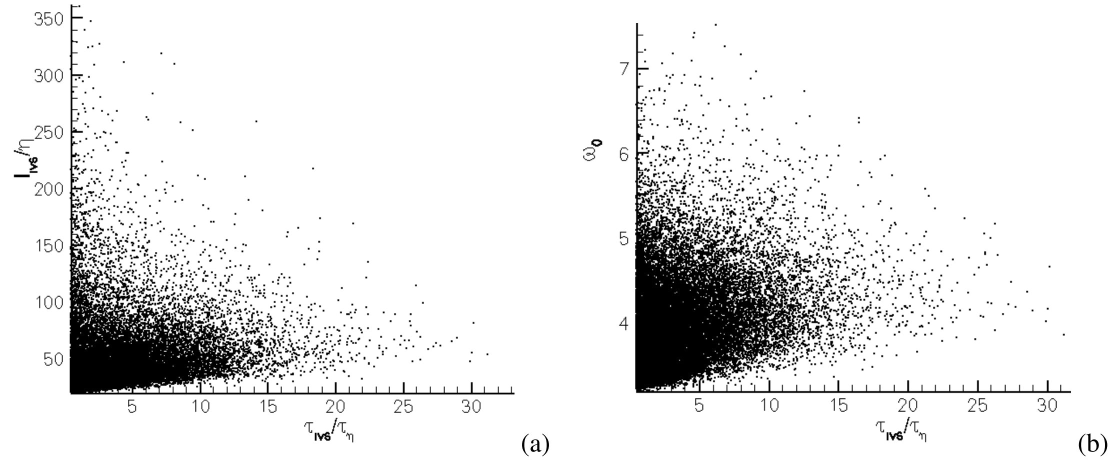


Figure 1. Scatter plots between the mean lifetime of the intense vorticity structures τ_{ivs}, and their mean length l_{ivs} (a), and between the mean lifetime of the structures τ_{ivs}, and their mean axial vorticity magnitude ω_0 (b). The life time is normalised by the Kolmogorov time scale τ_η,while the length and vorticity are normalised by the Kolmogorov length scale η and by the roor-mean-square vorticity ω'.

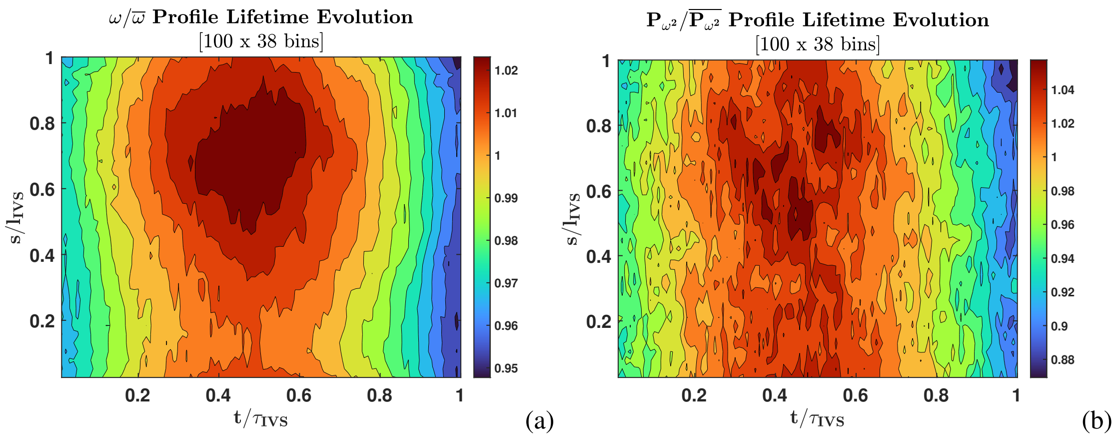


Figure 2. Lifetime dynamic maps of the intense vorticity structures showing the evolution of the axial vorticity magnitude ω_0 along its axis s, and along its entire living life t, where the time is normalised by the lifetime of each structure τ_{ivs} and the axial distance is normalised by the total length of each axis l_{ivs}: axial vorticity magnitude (a); enstrophy (temporal) rate of change (b).

the input forcing, $P = 10$, where the forcing f_i is imposed in the 2 wave numbers centred at $k_p = 2$. Thus the size of the computational box is always bigger than 4 times the longitudinal integral scale of turbulence.

The analysis of the IVS is carried out using the wormtracker algorithm described in (Ghira, Elsinga & da Silva 2025). The analysis is carried out in the statistically stationary phase of the simulations. Since the wormtracker algorithm used here is active at every time step of each simulation, the present analysis is able to process a very large number of samples/fields. These vary between $1400 \leq N_f \leq 12501$ instantaneous continuous fields, which corresponds to more than 6 integral time scales and to tens of Kolmogorov time scales.

RESULTS

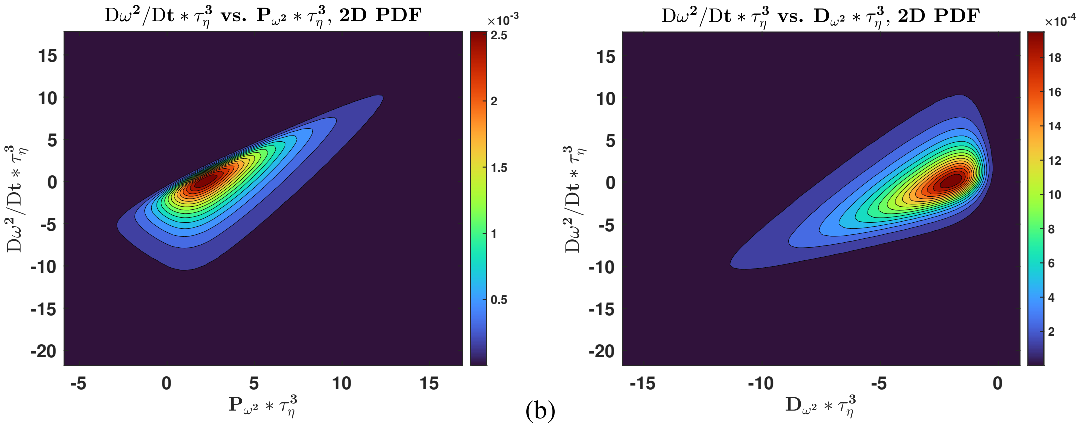
Figure 1 shows scatter plots between the mean lifetime of the intense vorticity structures τ_{ivs} and their mean length l_{ivs}, and between the mean lifetime of the structures τ_{ivs} and their mean axial vorticity magnitude ω_0. It is clear that there is no clear relation between these quantities, i.e. the IVS with bigger axial length do not live longer, nor the eddies with stronger axial vorticity. Moreover, virtually no IVS exist with very long lifetimes and with a small (length) size (or low enstrophy).

Figure 2 shows lifetime dynamic maps of the intense vorticity structures showing the evolution of the axial vorticity magnitude ω_0 along its axis s, and along its entire living life t. The maximum of these quantities occurs roughly at the middle of their lifes and at the middle of their axis, by the 'final life moments' are characterised by a sudden decrease of these quantities.

Finally, figure 3 show that throughout their life the enstrophy production and diffusion, are strongly correlated with the total enstrophy variation, implying that throughout their lives these mechanisms determine the evolution and dynamics of the IVS.

Many other similar quantities were analysed and showed that the 'death' of the IVS happens 'suddenly' and has no connection with any of the IVS characteristics. We also analysed spectra of the enstrophy governing terms along the axis of the IVS and as function of time. They do not show an increase of the level of enstrophy during time, previous to the death of the IVS, and the dominating frequencies acting upon the IVS display no relation with the ones associated with the growth of instabilities in the axis of the IVS.

Since the local worm characteristics do not affect their total life time, this suggests that the 'death' (break down or final dissipation) of these structures is caused by external flow



(b) (a)

Figure 3. Joint probability density functions of enstrophy (temporal) rate of change and axial enstrophy production (a) and, between enstrophy rate of change and axial vorticity diffusion (b). Both quantities are normalised by the Kolmogorov time scale, τ_η.

events, e.g., approaching and colliding nearby vortices, and not by instabilities observed at the axis of the structures.

CONCLUSIONS

A temporal tracking algorithm was used to follow in time millions of individual intense vorticity structures (IVS or 'worms') in homogeneous isotropic turbulence (HIT), from their 'births' to their 'deaths', and to analyse the axial characteristics, e.g., radius and axial vorticity profiles, as well as several turbulent variables acting at their axis, e.g. enstrophy production, as function of time. The results of the analysis of lifetime data from millions of 'worms', with Reynolds numbers up to $Re_\lambda = 190$, show that the local worm characteristics do not affect their total life time. This suggests that their 'deaths' i.e. the break down or final dissipation of these structures, is caused by external flow events, e.g., approaching nearby vortices, and not by instabilities observed at the axis of the structures.

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