Adding Visual Details Based on Low-Resolution Energy Cascade Ratios for Smoke Simulation

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(a) (b) (c) (d)

Figure 1: *Adding details for coarse grid simulations. (a) Linear interpolation. (b) Wavelet Turbulence. (c) Our method with* $\alpha = 0.1$ *everywhere. (d) Our method with* α *depending on the magnitude of velocity.*

Abstract

We propose a method for adding visual details to fluid animation while reducing noisy appearances. In grid-based fluid simulations, an issue is that while highly detailed fluids with small eddies can be obtained by increasing the number of grid cells, it costs much more computational time. To address this, various methods for adding details (or up-scaling resolutions) have been proposed. Those methods can generate fine animations quickly by adding high-frequency noises or external forces to coarse simulation results. However, those methods typically generate tiny eddies on a whole surface of fluid and the result appears too noisy. In this paper, we consider the distribution of kinetic energy in the spatial frequency domain and then apply it to two existing methods for adding details. By using our method, noises or external forces can be added to the appropriate positions of fluids and consequently natural-looking details can be achieved.

Keywords: Energy Cascade, Wavelet Turbulence, Vorticity Confinement

Concepts: •**Computing methodologies** → **Physical simulation;**

1 Introduction

In fluid simulation, there is a trade-off between computational accuracy and the run-time cost. Computation time increases as results increase in accuracy. To address this issue, various methods for adding details (or up-scale resolutions) have been proposed. By using these methods, detailed fluid behaviors can be obtained from coarse simulation results calculated using a low-res grid. Compared to actual high-res simulations, however, results are *too noisy* in appearance, having small eddies or noise on a surface of the fluid. One cause for this, which is addressed here, is that those methods do not consider the energy cascade of low-res simulation itself and then add noise uniformly to the whole region of a velocity field. To reduce the noisy appearance in the addition of details for smoke simulation, we focus on physical properties of turbulence that are not considered by previous methods. Specifically, from low-res simulation results, we calculate the energy cascade ratio in the spatial frequency domain and then add noise or eddies to appropriate positions of high-res fluids. This enables the reduction of the noisy appearances seen in previous methods.

2 Related Work

In grid-based fluid simulation, many methods for adding details have been proposed. There are two types of methods: One is to introduce eddies without changing the grid resolution, and the other is to add high-frequency details by increasing the grid resolution. Vorticity Confinement [Fedkiw et al. 2001] introduces external forces that produce eddies into simulated fluid velocities. This method generates fine details that cannot be produced by the original simulation. However, the result looks too noisy, due to the addition of eddies to a whole surface of fluid uniformly. Wavelet Turbulence [Kim et al. 2008] is a representative method for up-scaling resolution using noise function, which synthesizes high frequency noises to a coarse velocity field based on Kolmogorov's five-thirds law [Kolmogorov 1941]. However, in comparison with actual high-res simulation results, the result of adding details is too noisy.

3 Our Approach

Our method for adding details reflects the physical property of turbulence by computing the frequency ratio of the kinetic energy cas-

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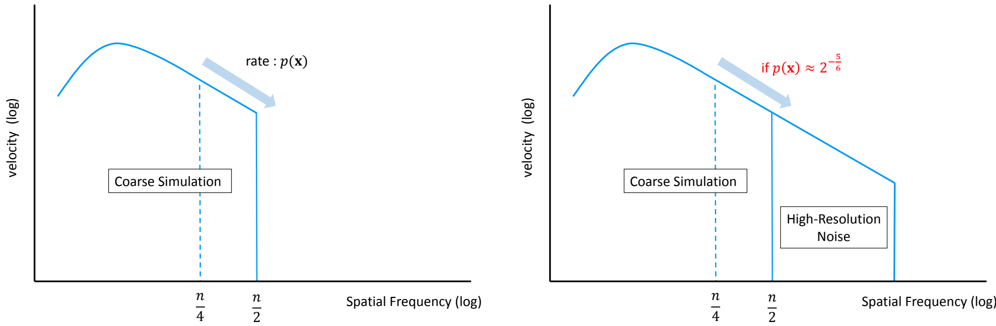


(a) (b)

Figure 2: *Spatial frequency distribution of kinetic energy. (a) In coarse simulation on n^3 grid, eddies up to $\frac{n}{2}$ frequency can be represented. (b) If the cascade ratio follows Kolmogorov's law $2^{-\frac{6}{5}}$, we synthesize high-frequency noise turbulences.*

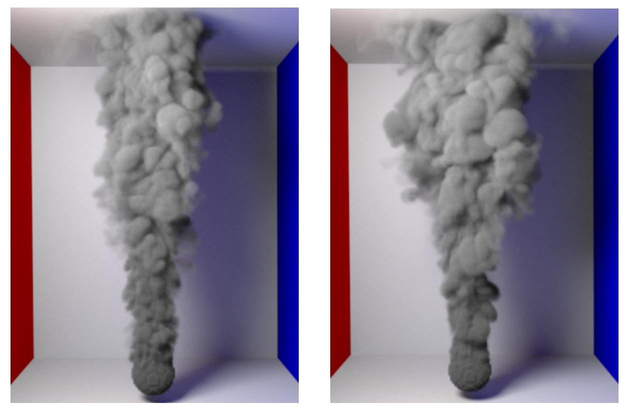
cade from low-res simulation and by using it to add highly detailed noises or eddies. Since we use only one parameter, we can easily control the amount of detail in fluid animation, making the design of fluid animation simple. In addition, our method to evaluate the energy cascade is easy to implement and can be combined with a variety of existing methods for adding details. Our algorithm consists of the following steps:

1. Compute the ratio of energy cascade (cascade ratio) for each cell in low-res grid.
2. Compare cascade ratio and Kolmogorov's five-thirds law, which represent turbulent energy distribution in spatial frequency domain.
3. For each cell, the procedure of adding details in the original method is only applied if the cascade ratio follows Kolmogorov's five-thirds law.

The above method will add the details to the appropriate positions of the velocity grid alleviating the noisy appearance of fluid. We also define a parameter to determine how close the cascade ratio is to Kolmogorov's law. With this parameter we can easily change the amount of noise to add. To determine whether the ratio follows Kolmogorov's law or not, we calculate a value of cascade ratio divided by the ideal value of Kolmogorov's law. We then examine if such a value is in the range $[1+\alpha, 1-\alpha]$, where α is determined by either of two methods: One is to set a fixed value by a user, the other is to set dynamically in each grid, depending on the magnitude of its velocity. The latter is based on Reynold's number, which means that the occurrence probability of turbulence is proportional to the flow speed. We integrate this algorithm into two existing methods for adding details: Wavelet Turbulence and Vorticity Confinement.

For application to Wavelet Turbulence, we need to make a noise texture before the up-scaling operation. We execute wavelet decomposition to a coarse velocity field, and compute cascade ratio. If the ratio follows Kolmogorov's law, we synthesize the noise texture based on the law (see Figure 2). Otherwise, we simply apply a linear interpolation to a low-res velocity field. Figure 1 shows the results of up-scaling resolution with Wavelet Turbulence and our method. Compared to the original Wavelet Turbulence result, in which high-frequency noises appear even in laminar flows on the lower part of fluid, our method can control noise so it does not appear on the lower part of the fluid.

We also apply our method to Vorticity Confinement in the coarse fluid simulation. For each frame of the simulation, we compute the cascade ratio from original simulation. In only places where the ratio follows the law we add external forces, to produce eddies. Figure 3 shows simulation results using Vorticity Confinement with



(a) (b)

Figure 3: *(a) Vorticity Confinement. (b) Vorticity Confinement with our cascade evaluation.*

and without our cascade evaluation. It can be seen that larger eddies appear in our method.

4 Conclusion

In this paper, we have proposed a method to apply the ratio of kinetic energy cascade to methods of adding detail to smoke simulation. As a result, our method can improve the noise appearance and makes it appear more natural. In future work we want to combine this cascade evaluation with other methods for adding details and apply to other types of fluids such as liquids.

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