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Shock-turbulence interactions at high turbulence intensities. (English) Zbl 1419.76358

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Summary: Shock-turbulence interactions are investigated using well-resolved direct numerical simulations (DNS) and analysis at a range of Reynolds, mean and turbulent Mach numbers (R_λ, M and M_t, respectively). The simulations are shock and turbulence resolving with R_λ up to 65, M_t up to 0.54 and M up to 1.4. The focus is on the effect of strong turbulence on the jumps of mean thermodynamic variables across the shock, the shock structure and the amplification of turbulence as it moves through the shock. Theoretical results under the so-called quasi-equilibrium (QE) assumption provide explicit laws for a number of statistics of interests which are in agreement with the new DNS data presented here as well as all the data available in the literature. While in previous studies turbulence was found to weaken jumps, it is shown here that stronger jumps are also observed depending on the regime of the interaction. Statistics of the dilatation at the shock are also investigated and found to be well represented by QE for weak turbulence but saturate at high turbulence intensities with a Reynolds number dependence also captured by the analysis. Finally, amplification factors are found to present a universal behaviour with two limiting asymptotic regimes governed by $(M-1)$ and $K = M_t/R_\lambda^{1/2}(M-1)$, for weak and strong turbulence, respectively. Effect of anisotropy in the incoming flow is also assessed by utilizing two different forcing mechanisms to generate turbulence.

MSC:

76F65 Direct numerical and large eddy simulation of turbulence
76F50 Compressibility effects in turbulence
76L05 Shock waves and blast waves in fluid mechanics

Keywords:

compressible turbulence; shock waves; turbulence simulation

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References:

[1] Agui, J. H.; Briassulis, G.; Andreopoulos, Y., Studies of interactions of a propagating shock wave with decaying grid turbulence: velocity and vorticity fields, J. Fluid Mech., 524, 143-195, (2005) · Zbl 1060.76500

[2] Andreopoulos, Y.; Agui, J. H.; Briassulis, G., Shock wave-turbulence interactions, Annu. Rev. Fluid Mech., 32, 309-345, (2000) · Zbl 0988.76048

[3] Barenblatt, G. I., Scaling, (2003), Cambridge University Press

[4] Barre, S.; Alem, D.; Bonnet, J. P., Experimental study of a normal shock/homogeneous turbulence interaction, AIAA J., 34, 968-974, (1996)

[5] Batchelor, G. K., The Theory of Homogeneous Turbulence, (1953), Cambridge University Press · Zbl 0053.14404

[6] Boukharfane, R.; Bouali, Z.; Mura, A., Evolution of scalar and velocity dynamics in planar shock-turbulence interaction, Shock Waves, 28, 6, 1117-1141, (2018)

[7] Chisnell, R. F., The normal motion of a shock wave through a non-uniform one-dimensional medium, Proc. R. Soc. Lond. A, 232, 1190, 350-370, (1955) · Zbl 0068.19201

[8] Donzis, D. A., Amplification factors in shock-turbulence interactions: effect of shock thickness, Phys. Fluids, 24, (2012)

[9] Donzis, D. A., Shock structure in shock-turbulence interactions, Phys. Fluids, 24, (2012)

[10] Donzis, D. A.; Jagannathan, S., Fluctuations of thermodynamic variables in stationary compressible turbulence, J. Fluid Mech., 733, 221-244, (2013) · Zbl 1294.76183

[11] Freund, J. B., Proposed inflow/outflow boundary condition for direct computation of aerodynamic sound the vorticity jump across a shock in a non-uniform flow, AIAA J., 35, 4, 740-742, (1997) · Zbl 0903.76081

[12] Gatski, T. B.; Bonnet, J.-P., Compressibility, Turbulence and High Speed Flow, (2009), Elsevier

[13] Goldenfeld, N., Roughness-induced critical phenomena in a turbulent flow, Phys. Rev. Lett., 96, (2006)

[14] Grant, H. L.; Nisbet, I. C. T., The inhomogeneity of grid turbulence, J. Fluid Mech., 2, 3, 263-272, (1957)

[15] Hannappel, R.; Friedrich, R., Direct numerical-simulation of a Mach-2 shock interacting with isotropic turbulence, Appl. Sci. Res., 54, 205-221, (1995) · Zbl 0853.76047

[16] Hesselink, L.; Sturtevant, B., Propagation of weak shocks through a random medium, J. Fluid Mech., 196, 513-553, (1988)

[17] Honkan, A.; Andreopoulos, J., Rapid compression of grid-generated turbulence by a moving shock-wave, Phys. Fluids, 4, 11, 2562-2572, (1992)

[18] Inokuma, K.; Watanabe, T.; Nagata, K.; Sasoh, A.; Sakai, Y., Finite response time of shock wave modulation by turbulence, Phys. Fluids, 29, 5, (2017)

[19] Jacquin, L.; Cambon, C.; Blin, E., Turbulence amplification by a shock wave and rapid distortion theory, Phys. Fluids, 3, 2539, (1993) · Zbl 0799.76029

[20] Jagannathan, S.; Donzis, D. A., Reynolds and Mach number scaling in solenoidally-forced compressible turbulence using high-resolution direct numerical simulations, J. Fluid Mech., 789, 669-707, (2016)

[21] Jamme, S.; Cazalbou, J.-B.; Torres, F.; Chassaing, P., Direct numerical simulation of the interaction between a shock wave and various types of isotropic turbulence, Flow Turbul. Combust., 68, 227-268, (2002) · Zbl 1051.76576

[22] Jimenez, J., Turbulent velocity fluctuations need not be Gaussian, J. Fluid Mech., 376, 139-147, (1998) · Zbl 0922.76234

[23] Kitamura, T.; Nagata, K.; Sakai, Y.; Ito, Y., Rapid distortion theory analysis on the interaction between homogeneous turbulence and a planar shock wave, J. Fluid Mech., 802, 108-146, (2016) · Zbl 1456.76057

[24] Kovasznay, L. S. G., Turbulence in supersonic flow, J. Aerosp. Sci., 20, 10, 657-674, (1953) · Zbl 0051.42201

[25] Larsson, J.; Bermejo-Moreno, I.; Lele, S. K., Reynolds- and Mach-number effects in canonical shock-turbulence interaction, J. Fluid Mech., 717, 293-321, (2013) · Zbl 1284.76241

[26] Larsson, J.; Lele, S. K., Direct numerical simulation of canonical shock/turbulence interaction, Phys. Fluids, 21, (2009) · Zbl 1183.76296

[27] Lee, S.; Lele, S. K.; Moin, P., Direct numerical simulation of isotropic turbulence interacting with a weak shock wave, J. Fluid Mech., 251, 533-562, (1993)

[28] Lee, S.; Lele, S. K.; Moin, P., Interaction of isotropic turbulence with shock waves: effect of shock strength, J. Fluid Mech., 340, 225-247, (1997) · Zbl 0899.76194

[29] Lele, S. K., Compact finite-difference schemes with spectral-like resolution, J. Comput. Phys., 103, 16-42, (1992) · Zbl 0759.65006

[30] Lele, S. K., Shock-jump relations in a turbulent flow, Phys. Fluids, 4, 12, 2900-2905, (1992) · Zbl 0762.76050

[31] Livescu, D.; Ryu, J., Vorticity dynamics after the shock-turbulence interaction, Shock Waves, 26, 3, 241-251, (2016)

[32] Mahesh, K.; Lee, S.; Lele, S. K.; Moin, P., Interaction of an isotropic field of acoustic waves with a shock wave, J. Fluid Mech., 300, 383-407, (1995) · Zbl 0858.76074

[33] Mahesh, K.; Lele, S. K.; Moin, P., The influence of entropy fluctuations on the interaction of turbulence with a shock wave, J. Fluid Mech., 334, 353-379, (1997) · Zbl 0899.76193

[34] Moeckel, W. E.

[35] Mohamed, M. S.; Larue, J. C., The decay power law in grid-generated turbulence, J. Fluid Mech., 219, 195-214, (1990)

[36] Moin, P.; Mahesh, K., Direct numerical simulation: A tool in turbulence research, Annu. Rev. Fluid Mech., 30, 539-578, (1998) · Zbl 1398.76073

[37] Monin, A. S.; Yaglom, A. M., Statistical Fluid Mechanics, II, (1975), MIT Press

[38] Moore, F. K.

[39] Moser, R. D., On the validity of the continuum approximation in high Reynolds number turbulence, Phys. Fluids, 18, 7, (2006)

[40] Noullez, A.; Frisch, U.; Wallace, G.; Lempert, W.; Miles, R. B., Transverse velocity increments in turbulent flow using the relief technique, J. Fluid Mech., 339, 287-307, (1997)

[41] Obukhov, A. M., The structure of the temperature field in a turbulent flow, Izv. Akad. Nauk. SSSR, 13, 58-69, (1949)

[42] Quadros, R.; Sinha, K.; Larsson, J., Kovasznay mode decomposition of velocity-temperature correlation in canonical shock-turbulence interaction, Flow Turbul. Combust., 97, 787-810, (2016)

[43] Quadros, R.; Sinha, K.; Larsson, J., Turbulence energy flux generated by shock/homogeneous-turbulence interaction, J. Fluid Mech., 796, 113-157, (2016)

[44] Ribner, H. S.

[45] Ribner, H. S.

[46] Ryu, J.; Livescu, D., Turbulence structure behind the shock in canonical shock-vortical turbulence interaction, J. Fluid Mech., 756, (2014)

[47] Sagaut, P.; Cambon, C., Homogeneous Turbulence Dynamics, (2008), Cambridge University Press · Zbl 1154.76003

[48] Schumacher, J.; Scheel, J. D.; Krasnov, D.; Donzis, D. A.; Yakhot, V.; Sreenivasan, K. R., Small-scale universality in fluid turbulence, Proc. Natl Acad. Sci. USA, 111, 30, 10961-10965, (2014) · Zbl 1355.76027

[49] Schumacher, J.; Sreenivasan, K. R.; Yakhot, V., Asymptotic exponents from low-Reynolds-number flows, New J. Phys., 9, 89, (2007)

[50] Tanaka, K.; Watanabe, T.; Nagata, K.; Sasoh, A.; Sakai, Y.; Hayase, T., Amplification and attenuation of shock wave strength caused by homogeneous isotropic turbulence, Phys. Fluids, 30, 3, (2018)

[51] Taylor, G. I., Turbulence in a contracting stream, Z. Angew. Math. Mech., 15, 91-96, (1935) · Zbl 61.0927.01

[52] Thompson, P. A., Compressible Fluid Dynamics, (1984), McGraw-Hill

[53] Velikovich, A. L.; Huete, C.; Wouchuk, J. G., Effect of shock-generated turbulence on the Hugoniot jump conditions, Phys. Rev. E, 85, (2012) · Zbl 1248.76106

[54] Whitham, G. B., On the propagation of shock waves through regions of non-uniform area or flow, J. Fluid Mech., 4, 4, 337-360, (1958) · Zbl 0081.41501

[55] Widom, B., Equation of state in the neighborhood of the critical point, J. Chem. Phys., 43, 11, 3898-3905, (1965)

[56] Williams, J. E. F.; Howe, M. S., On the possibility of turbulent thickening of weak shock waves, J. Fluid Mech., 58, 3, 461-480, (1973) · Zbl 0258.76039

[57] Wouchuk, J. G.; de Lira, C. H. R.; Velikovich, A. L., Analytical linear theory for the interaction of a planar shock wave with an isotropic turbulent vorticity field, Phys. Rev. E, 79, (2009)

[58] Yakhot, V.; Donzis, D. A., Emergence of multiscaling in a random-force stirred fluid, Phys. Rev. Lett., 119, (2017)

[59] Yakhot, V.; Donzis, D. A., Anomalous exponents in strong turbulence, Phys. D, 384-385, 12-17, (2018)

[60] Zank, G. P.; Zhou, Y.; Matthaeus, W. H.; Rice, W. K. M., The interaction of turbulence with shock waves: a basic model, Phys. Fluids, 14, 3766-3774, (2002) · Zbl 1185.76417

[61] Zeldovich, Y. B.; Raizer, Y. P., Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena, (2002), Dover