Influence Of Acoustic Field On Turbulence Characteristics

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ABSTRACT
A major problem hindering the development of low NOx gas turbines has been the occurrence of thermoacoustic instabilities. Since combustion in engines is controlled by turbulence, it appears necessary that to be able to predict and model the influence of acoustic waves on combustion, one must first understand the direct influence of acoustic oscillations on turbulence. The present work aims at studying how acoustic energy is distributed on the turbulence spectrum. In addition to the effect on the turbulence intensity, it is important to elucidate the modes of energy transfer within the spectrum, depending on the excitation frequency. The behaviour of a controlled grid generated turbulent field under acoustic excitation has been investigated experimentally. Although difficulties in the experiments limited the accuracy and extent of the measurements, it was found that the acoustic waves passing through the turbulent field impose a velocity fluctuation that appears as a strong peak in the spectrum. In this sense, sound perturbs the isotropy of the turbulence. However, the turbulent kinetic energy remained nearly unchanged. These preliminary conclusions can only exclude a major influence of the acoustics on turbulence, while tiny anisotropies might have not been detected by our measurement chain.

INTRODUCTION

Turbulence - acoustic interactions in jets and shear layers have been largely investigated in literature ([1][2][3] amongst others). Excitation of shear or mixing layers are described and analysed, when forcing occurs at characteristic frequencies. As a consequence the complete dynamic field development is affected. Indeed, shear and mixing layers are the mechanisms which in turn generate turbulence at lower scales. Therefore these studies focus on the action of pressure waves on the source of turbulence, but the direct effect on turbulence itself (on a turbulence spectrum for example) does either not appear directly or is overridden. The question of how acoustic energy is distributed on the turbulence spectrum remains. In addition to amplification of the turbulence intensity, it is important to elucidate the spectral energy transfer depending on which region of the spectrum the excitation is applied. To our knowledge, no study concentrated on these aspects. Since combustion in industrial applications is always controlled by turbulence, it appears necessary that to be able to capture and model the influence of acoustic waves on combustion, one must first understand the direct influence of acoustic oscillations on turbulence.

TURBULENCE MODELLING OF THE DECAY OF ACOUSTIC WAVES

<u>The effect of acoustics on the kinetic energy</u>

To investigate acoustics-turbulence interaction and the effect on production and dissipation of turbulence energy, we have chosen to perturb a grid-generated turbulence field. In this case the whole turbulence kinetic energy is generated at the grid, and from the grid on it decays uniformly. Therefore, any further increase of the turbulence energy should be related to acoustics. In accordance with the Lighthill analogy, we assume that, far from the source, acoustics does not affect density, but mostly the velocity field. In the following, it is shown how the Reynolds stresses are affected by mean shears at different regimes.

Mean velocity gradients, such as the one generated by acoustic waves, have an effect on both production and dissipation of turbulence energy. The effect that different frequencies and amplitudes of the waves have on development of turbulence can be investigated on the basis of the Reynolds-stresses equations:

$$\frac{D}{DT}\left\langle u_i u_j \right\rangle + \frac{\partial}{\partial x_k}\left\langle u_i u_j u_k \right\rangle = P_{ij} + \Pi_{ij} - \varepsilon_{ij} - \nu\nabla^2\left\langle u_i u_j \right\rangle \quad (1)$$

where:

$$P_{ij} = -\left\langle u_i u_k \right\rangle \frac{\partial\left\langle U_j \right\rangle}{\partial x_k} - \left\langle u_j u_k \right\rangle \frac{\partial\left\langle U_i \right\rangle}{\partial x_k} \quad (2)$$

is the production tensor

$$\Pi_{ij} = -\frac{1}{\rho}\left\langle u_i \frac{\partial p'}{\partial x_j} + u_j \frac{\partial p'}{\partial x_i} \right\rangle \quad (3)$$

is the velocity-pressure-gradient tensor

$$\varepsilon_{ij} = 2\nu\left\langle \frac{\partial u_i}{\partial x_k}\frac{\partial u_j}{\partial x_k} \right\rangle \quad (4)$$

is the dissipation tensor. The last two terms in Eq. (4) and the second L.H.S. terms in Eq. (1) are not in closed form and have to be modelled.

Production of turbulence kinetic energy should be expected in case of convolution of velocity fluctuations with mean velocity gradients (Eq. (2)). In general, when dealing with grid-generated turbulence, the mean field does not, or should not, have mean velocity gradients, and thus this term is not responsible for any production of turbulence. Of course such an effect should be expected in combustion chambers, where mean velocity gradients are not negligible especially in the proximity of the walls and in the recirculation zones. In this case, when an acoustic wave is moving in the same direction as the mean flow (i.e. x-direction) the production term becomes:

$$P_{11} = -2\langle u^2 \rangle \frac{\partial \langle U \rangle}{\partial x} \tag{5}$$

This is either positive or negative depending on the sign of the gradient. If the time of the average is shorter than the acoustic wave length, the mean velocity (U) due to acoustics will fluctuate in time, and thus velocity fluctuations could be seen as responsible for the production of mean turbulent kinetic energy. However, such a production is due to the averaging, since if one integrates (5) over the period of the acoustic wave the overall production will vanish. For this reason, despite of the integration time, we do not expect this term to be responsible for any production of turbulent energy.

The velocity-pressure-gradient term (eq. (3)) can be decomposed into two terms:

$$\Pi_{ij} = R_{ij} - \frac{\partial T_{kij}^{(p)}}{\partial x_k} \tag{6}$$

where:

$$R_{ij} = \left\langle \frac{p'}{\rho}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right\rangle \tag{7}$$

is the Pressure-Rate-of-Strain tensor, and

$$T_{kij}^{(p)} = \frac{1}{\rho}\langle u_i p' \rangle \delta_{jk} + \frac{1}{\rho}\langle u_j p' \rangle \delta_{ik} \tag{8}$$

is the Pressure-transport tensor.

Both terms need modelling, but if compressibility effects are negligible, the trace of Rij is zero, and consequently, it does not contribute to the production of turbulent kinetic-energy. However, the off-diagonal terms provide to redistribute energy among the Reynolds stresses.

A decomposition of the pressure transport tensor can be achieved by defining the following Poisson equation for pressure:

$$\frac{1}{\rho}\nabla^2 p' = -2\frac{\partial \langle U_i \rangle}{\partial x_j}\frac{\partial u_j}{\partial x_i} - \frac{\partial^2}{\partial x_i \partial x_j}\left(u_i u_j - \langle u_i u_j \rangle\right) \tag{9}$$

on the basis of this equation, pressure can be split in three contribution: rapid, slow, and harmonic:

$$p' = p^{(r)} + p^{(s)} + p^{(h)} \tag{10}$$

where the rapid pressure satisfies:

$$\frac{1}{\rho}\nabla^2 p^{(r)} = -2\frac{\partial \langle U_i \rangle}{\partial x_j}\frac{\partial u_j}{\partial x_i} \tag{11}$$

the slow pressure satisfies:

$$\frac{1}{\rho}\nabla^2 p^{(s)} = -\frac{\partial^2}{\partial x_i \partial x_j}\left(u_i u_j - \langle u_i u_j \rangle\right) \tag{12}$$

and the harmonic contribution satisfies the Laplace equation

$$\nabla^2 p^{(h)} = 0 \tag{13}$$

on which are imposed the boundary conditions. Corresponding to each of the pressure terms it is possible to define a pressure-rate-of-strain tensor as:

$$R_{ij}^{(r,s,h)} = \left\langle \frac{p^{(r,s,h)}}{\rho}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right\rangle \tag{14}$$

In respect to acoustic waves, the most important term seems to be the Slow-Pressure-Rate-of-Strain tensor, whose behaviour has been used to study the decay of homogeneous anisotropic turbulence. In this case Eq. (12) is the only term in Eq. (14) that is non-zero. Rotta [4] modelled the decay of homogeneous anisotropic turbulence showing that it corresponds to a linear return to isotropy.

Oppositely, the Slow-Pressure-Rate-of-Strain tensor becomes negligible when time-dependent uniform velocity gradients perturb a homogeneous turbulence field [5]. This was studied and modelled by means of the Rapid-Distortion Theory. In this case, the Slow-Pressure-Rate-of-Strain is zero, and the evolution of turbulence is dominated by the Rapid-Pressure-Rate-of-Strain tensor.

Return to isotropy or rapid distortion?

Return to isotropy and rapid-distortion theory (RDT) are the two limit cases of the interaction of mean shear with turbulence. In the first case, anisotropic velocity gradients are superimposed onto a homogeneous field, and thus turbulence operates a redistribution of the energy among the different spatial direction (x, y, z) without affecting the production of kinetic energy. This theory is valid if the time scales associated to the anisotropy are rather large than the scale of turbulence. Pope [6] used the turbulence-to-mean-shear time scale ratio

$$\tau S = S\frac{k}{\varepsilon} \tag{15}$$

as a parameter to define whether an anisotropy was evolving accordingly to the RDT or to the return to isotropy. In Eq. (15)

$$S = \left(2\bar{S}_{ij}\bar{S}_{ij}\right)^{1/2} \tag{16}$$

is the mean strain rate, whose inverse is the time scale of the mean shear. When the ratio of Eq. [15] is arbitrary large, the mean shear is faster than the turbulence scales and the RDT theory can be used to describe their interaction. On the other side the evolution of turbulence will follow a path more similar to the return to isotropy when the ratio of Eq. (15) is close to zero, which requires that mean-shear time scales are slower than turbulence.

In the case of turbulence flames and their interaction with sound, acoustics frequencies are often in the range of 50-400 Hz [7], which correspond to scales longer than most of the turbulence scales observed in combustors. For this reason we expect to observe in the experiments a turbulence-acoustic interaction in accordance to the return to isotropy. If so, the turbulence kinetic energy should not be modified by acoustic waves, while there should be a redistribution of the energy along the different flow directions.

EXPERIMENTAL SET UP

The experimental apparatus is illustrated in figure 1. A grid-generated turbulence flow is generated by feeding a plenum chamber with compressed air. The plenum chamber is connected to a 50 mm diameter cylindrical tube. On the top of the cylindrical tube, a perforated plate is placed. The turbulent air flow generated is unconfined to avoid interactions with boundary layers and sound reflection at the walls. The plate is perforated with 1.1 mm holes and a porosity of 0.274. The apparatus is placed in a semi-anechoic chamber. Secondary air injection goes through a silicon oil atomizer and carries the seeding particles necessary for the LDV measurements. Acoustic excitation is provided by a compression driver mounted on a 50 cm long and 3' diameter tube. The acoustic driver is placed downstream of the flow in a manner that quasi-plane waves travel against the main flow direction. A sine wave generator coupled to a 300W amplifier controls frequency and amplitude of the acoustic excitation, which is evaluated by placing a microphone at a fixed position aside the flow. Velocity measurements are done by LDV.

RESULTS AND ANALYSIS

In grid-generated turbulent flow, the mean flow is constant, and the turbulence is nearly isotropic, so there is no production by mean shear and the turbulence just decays due to dissipation. There are no natural instability phenomena and it makes that type of flow well adapted to our purpose, namely to evaluate any productive or dissipative effect of acoustic waves on turbulence. Shortcomings due to the expected limitation of the apparatus (no wind tunnel were accessible) induced that locally isotropic and homogenous grid-generated turbulent conditions can only be achieved in the restricted area near the centreline and up to ca. z=45mm downstream. The turbulent characteristics of the field under acoustic excitation have been probed at two locations in the flow: 1) at z=30 mm, i.e. in the grid generated like type of turbulence; and 2) at z=155 mm, i.e. in the developed jet turbulence zone, and near the acoustic excitation tube exit where the waves are at highest amplitude.

Figure 2 shows the measurements of the kinetic energy of turbulence, k, as a function of excitation frequency. There is apparently very little effect of the acoustic excitation. The influence is now observed on the turbulence spectrum on the figures 3 and 4 for the measurement position at z=30 mm (grid generated type turbulence) and 155 mm (far field jet type turbulence) respectively. The spectra have the expected shape with the energy containing range followed by the cascade or inertial sub-range, and finally the dissipation range with an attenuation of the slope [8]. High frequency noise becomes important in the latter region as we approach the sampling frequency limit. This is typical of spectra obtained from LDV, where the complete measurement data set is re-sampled before the FFT algorithm is applied. The acoustic velocity oscillation is clearly seen on the spectra with a strong peak at the excitation frequency. The peak bandwidth seems to increase as the excitation frequency decreases, but it is only the logarithmic scaling which is misleading. Furthermore the apparently large width of the peak is only a result of the frequency resolution from the FFT calculation.

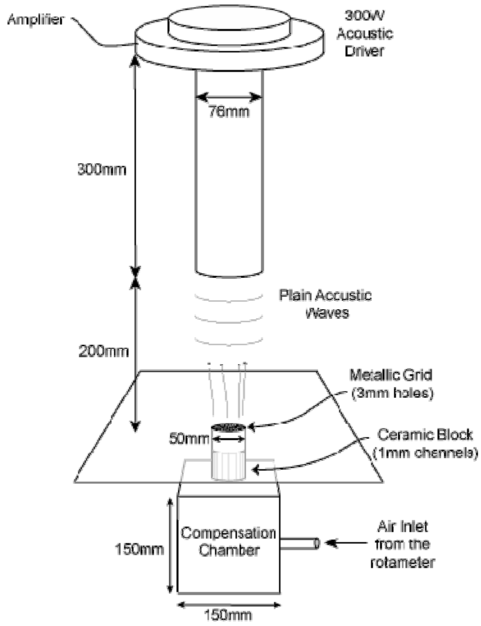

Figure 1: *Experimental set-up*

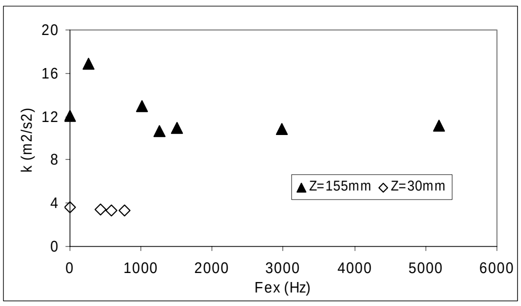

Figure 2: *Kinetic energy of turbulence as a function of excitation frequency*

The spectra obtained show little effect of the excitation, apart from the excitation peak itself. In the 5182 Hz case, the peak has disappeared from the spectrum, but as it will be discussed later, it is most probably not due to turbulence–acoustic interaction. The velocity fluctuation induced by the acoustic passing waves is noticeable on both cases, although for the 5182 Hz excitation the velocity fluctuation spectrum fails to produce a discernable peak. It indicates that this frequency excitation in the dissipation zone is not "absorbed" or dissipated, but most probably we have reached the resolution limit with this data rate. Even though the average data rate is according to Shannon criterion high enough to resolve this frequency, the combination of noisy signal (inherent to turbulent flows at high frequencies) and resampling of the time series, imposes a strong requirement on data rate and number of samples if one desires to investigate particular peaks high frequency zones with the LDV technique.

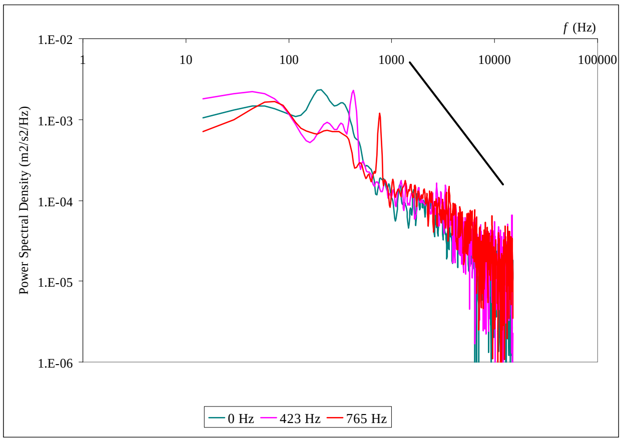

Figure 3: *Turbulent velocity spectrum at z=30mm*

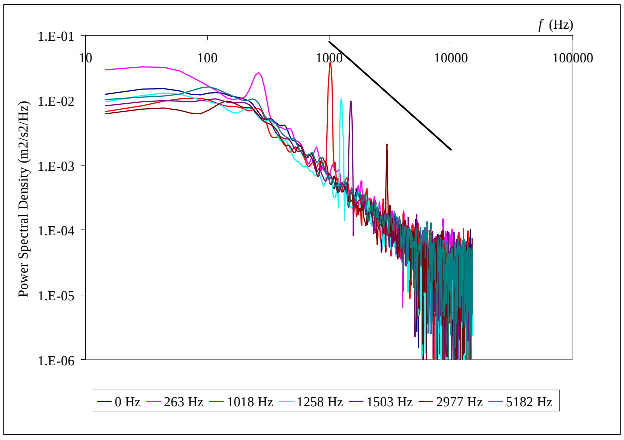

Figure 4: *Turbulent velocity spectrum at z=155mm*

From the spectra of figures 3 and 4 the effect of acoustic on turbulence seems to be rather different at the two sampling points. In particular, at z=30 mm the unperturbed velocity spectrum is not flat in the range from 200 to 500 Hz, and this might be due to secondary flows developing inside of the plenum which are not completely equalized. In fact at z=155 mm the same spectrum shows the expected flat behaviour in the same frequency range, suggesting that the secondary motions developed inside the plenum have been dissipated. However, it is worth noticing that acoustic has a rather different effect in the two cases: where the flow is less equalized (z=30mm, figure 3) acoustics seems to affect more the velocity spectrum, which loses part of its energy in the range affected by the secondary flow instabilities. At z=155mm (figure 4) instead acoustics does not seems to have any effect on the dynamic of turbulence that looks less perturbed than the previous case except for the peaks corresponding to the forcing frequencies. Moreover it suggests that acoustic forcing does exchange energy with the turbulence field.

Turbulence spectrum on the radial component of velocity, i.e. in the direction normal to the wave propagation indicate that no sign of the excitation can be felt on this component either at 30 mm or 155 mm, therefore no transfer of the added longitudinal motion to the transversal direction.

CONCLUSIONS

Literature on acoustic/turbulence interaction generally aims at the development of one or more shear layers under the action of acoustic perturbation. It was found that, depending on the frequency, both suppression and augmentation of field turbulence could be generated through the process of vortex formation. However, studies on the influence on the turbulence characteristics itself and the process through which energy is transferred and dissipated were not found. We focussed our study on this aspect by investigating the behaviour of a grid generated turbulent field under acoustic excitation. The excitation frequency was varied in a way to cover the three main regions of a turbulent spectrum. The acoustic waves passing through the turbulent field impose a velocity fluctuation that can be measured and appears as a strong peak in the spectrum. In this sense, sound perturbs the isotropy of the turbulence. Nevertheless the lack of effect on the kinetic energy of turbulence should confirm that the initial anisotropy decays following the path described by the return-to-isotropy theory. In this case the turbulent energy is not affected, while the energy of the anisotropy is redistributed among the stresses. Some difficulties in the experiments limited the accuracy and extent of the measurements. Therefore, these conclusions can only exclude a major influence of the acoustics on turbulence, while tiny anisotropies might have not been detected by our measurement chain.

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