LAMINAR-TURBULENT TRANSITION: THE EFFECT OF MODULATION ON THE EVOLUTION OF WAVES IN BOUNDARY LAYERS

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Summary. *The influence of streamwise modulation on the evolution of three-dimensional wavetrains in boundary layers is experimentally investigated. The results show that for slowly modulated wavetrains the first nonlinear signature a mean flow distortion that resembles the mean flow distortion observed in continuous wavetrains. At some stage of the nonlinear evolution all the modulated signals displayed a band of frequencies close to the subharmonic. The spanwise wavenumber of this band was similar to the spanwise wavenumber of the mean flow distortion in continuous wavetrain. Some of the results suggest that the mechanisms that produce the mean flow distortion in three-dimensional continuous wavetrains might provide a deterministic seed for subharmonic resonance. Others indicated that subharmonic band is detached from the fundamental one.*

Key-words: *Hydrodynamic instability, laminar-turbulent transition, boundary layers, hot-wire anemometry, experimental fluid mechanics*

1. INTRODUCTION

Laminar turbulent transition in boundary layers is an active research subject in fluid mechanics. The early stages of the transition process are very well modelled by the linear instability theory (Lin, 1995). Experimental (Kachanov, 1994), numerical (Rist and Fasel, 1995) and theoretical work (Craik, 1971 and Herbert, 1988) have shown that nonlinear later stages frequently involve mechanics of either fundamental or subharmonic resonance. For instance the resonance models have been able to describe in detail the nonlinear evolution of small amplitude plane regular wavetrains.

However, the transition process that occurs in natural conditions rarely involves plane regular waves. On the contrary, in such situation the waves are frequently highly three-dimensional and modulated. It has been shown (Medeiros, 1999, Medeiros and Mendonça, 1999 and Stemmer et al., 1998) that for three-dimensional wavetrains the early nonlinear stages is dominated by a mechanism that generates longitudinal vortices.

These vortices redistribute the streamwise momentum and produce streaks of higher and lower streamwise velocity. The picture can be described as a mean flow distortion with a spanwise structure. Such mechanism is similar to the lift up mechanism that has been observed in the so called by pass transition (Heningsson et al. 1993) and the oblique transition (Elofsson and Alfredsson, 1997).

Other types of three-dimensional waves have been studies in connection to the natural transition process. One such three-dimensional wave is the wavepacket generated from a point source excitation (Gaster and Grant, 1975 and Gaster, 1975). The results have shown that the nonlinear evolution of wavepackets involves the appearance of waves of frequency close to the subharmonic frequency of the dominant fundamental modes of the packet. However, experimental results by Medeiros and Gaster (1999a and 1999b) have shown that subharmonic resonance alone cannot explain the experimental observations. It appears that some mechanism of production of low-frequency waves would have to be present.

Further studies have suggested that the production of low-frequency waves in the packet might be linked to the generation of streaks in the three-dimensional wavetrain. However, this conjecture is as yet unproven. The effect of streamwise modulation on the nonlinear evolution of three-dimensional wavetrains is currently being investigated. This paper presents some of the experimental results obtained.

2. METHODOLOGY

The investigation is based on a comparative study of the evolution of wavetrains with different degrees of streamwise modulation. The different wave systems range from a wavepacket generated from a pulse excitation to a wavetrain generated from a harmonic point source.

The experiments were conducted in the low-turbulence wind tunnel of the University of Cambridge [1]. The tunnel had a free stream turbulence level of about 0.00817.4 m/s. The boundary layer to be studied developed on a flat aluminium plate with an elliptical nose. Trailing flaps were adjusted to ensure an almost zero pressure gradient along the plate. Details of the base flow are given by Medeiros (1996). The disturbances were produced using a loudspeaker embedded in the plate at 203mm from the leading edge. The loudspeaker was driven by a signal generated from a computer. Hot-wire anemometry was used to record the streamwise velocity fluctuations. The hot-wire probe was mounted on three-dimensional traverse gear that was controlled by the computer. Measurements were taken at different positions building a three-dimensional view of streamwise velocity field. 128 records for and identical disturbance were obtained at each measuring station. The 128 signals were later ensemble averaged in order to improve the signal to noise ratio.

The wavetrains with different degrees of modulation had an identical base frequency, namely 200Hz. This frequency was among the most amplified frequencies in the Reynolds number range investigated. The signal representing a continuous wavetrain was a fairly short one; just long enough to behave like a continuous one. To produce the modulated disturbances different triangular modulating envelopes were applied to the time series that drove the loudspeaker. The shortest signal was a wavepacket generated from a pulse excitation (Medeiros and Gaster, 1999a).

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[1] Now located at the Queen Mary and Westfield College

3. RESULTS

Figure 1 displays hot-wire records taken along the centreline of the plate. The results are shown for different degrees of modulation at different downstream positions. At x=1000mm, all signals have similar peak to peak amplitude. At x=1100mm and x=1200 the top signal representing a continuous wavetrain displays a mean flow distortion. A similar distortion is seen for the weakly modulated signals (B and C). At these stations the wavepacket displays its characteristic nonlinear signature, namely, the loss of one ripple at the trailing edge. The view point to a pattern linking the mean flow distortion of the wavetrain to the loss of a ripple in the packet.

Figure 2 displays the spectra of the signals in figure 1. For the wavetrain the spectra display a large component with frequency close to zero. For the weakly modulated wavetrains a signal of very low frequency is also observed which appears to be linked to mean flow distortion in the wavetrain. For these packets the stronger the modulation the wider the spectral band of low frequencies. This is connected to the fact that for the modulated wavetrains the mean flow distortion is more localised in time and therefore wider in the spectrum.

For the highly modulated signals the nonlinearity is characterised by a structure of the signals. The experiment was therefore extended to cover a number of spanwise stations for each streamwise measuring stations shown in figure 1.

For comparison with results for continuous wavetrain the more detailed experimental results by Medeiros are used. Figure 3 shows the nonlinear evolution of a wavetrain in spectral domain. Initially the mean flow distortion appears as a signal of both low frequency and low spanwise wave number. At later stages higher spanwise number wave numbers appear.

Figures 4 to 6 show the nonlinear evolution of the modulated signals in two-dimensional Fourier space. The pictures compare the signals of different degrees of modulation for each streamwise position. For all modulated signals in the nonlinear regime a signal close to subharmonic eventually appears. Both the frequency and the spanwise wavenumber of this signal are very similar. The spanwise wavenumber is also similar to that of the low frequency signal of the continuous wavetrain at the same streamwise station x=1100mm.

Following the conjecture that the subharmonic resonance would be seeded by a localised mean flow distortion, one would expect the subharmonic signal to be fed from the lower frequencies. However, it appears that the subharmonic band is detached from the fundamental rather than from a lower frequency band. This is particularly clear for the shorter signals.

4. DISCUSSION

All modulated signals displayed, at some stage of the nonlinear development, a signal with frequency close to subharmonic. The more slowly modulated signal also showed, at an earlier stage, a mean flow distortion that resembled the mean flow distortion observed in three-dimensional wavetrains. The spanwise wavenumber of the subharmonic signals was similar to the spanwise wavenumber of the mean flow distortion of the three-dimensional wavetrain. On the other hand the subharmonic band appeared to detach from the fundamental band rather than from the mean flow distortion.

The signal studied have very low amplitude. Despite the low level of free-stream turbulence in the flow, the signals were relatively noisy, The noisy content was particularly high at the very low frequencies that characterised the mean flow distortion. This made it difficult to interpret the results. Higher resolution in the spanwise direction would also have been helpful. Clearer results could be obtained by direct Navier/Stokes simulations, but a large number of simulations might be needed to provide enough data for analysis.

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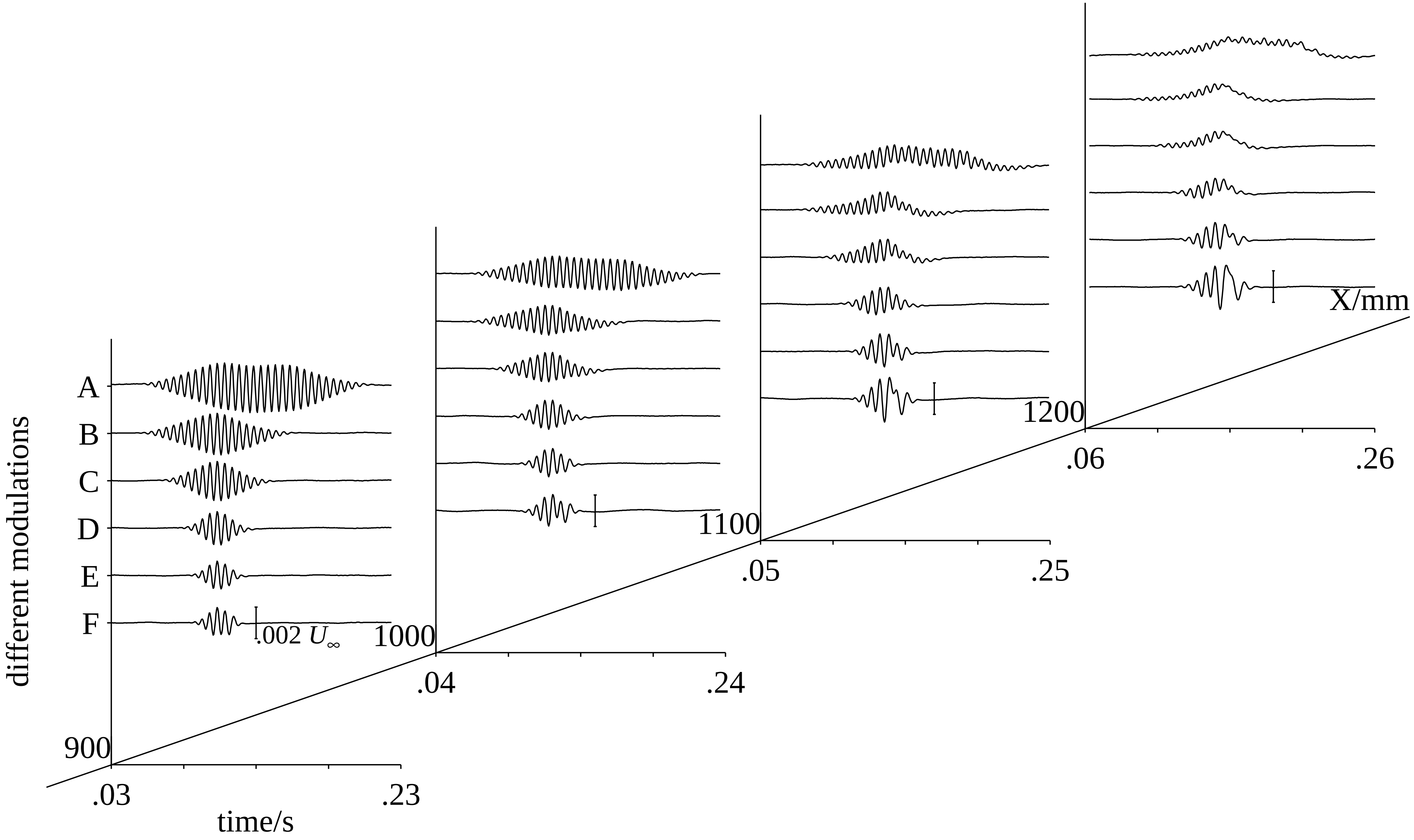

Figure 1: Nonlinear evolution of TS waves with different modulation envelope. Measuremnts taken along the centreline at $y = .6\delta^*$.

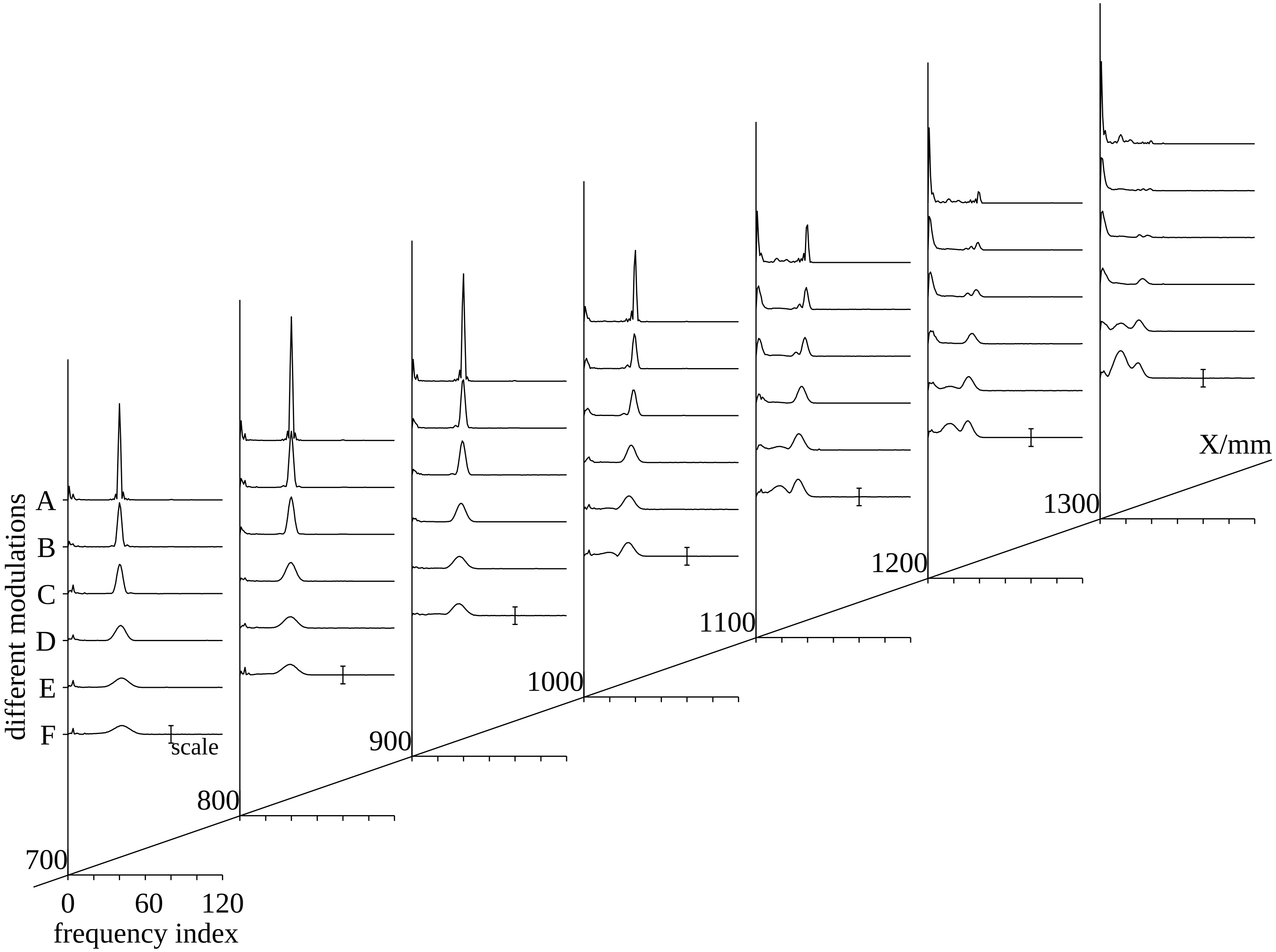

Figure 2: Signals of figure 1 in Fourier space.

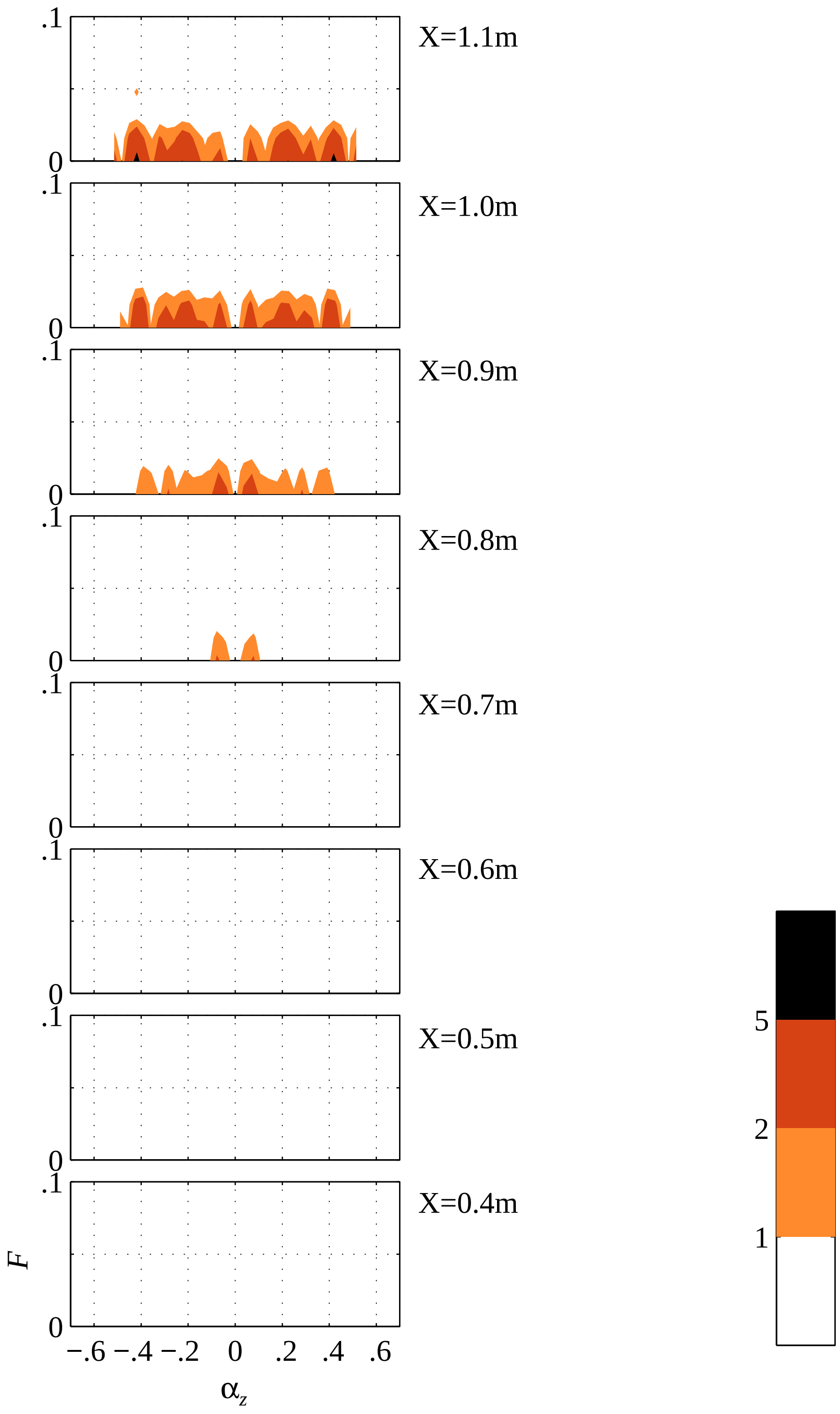

Figure 3: Evolution of the mean flow distortion in a wavetrain emanating from a harmonic point source. Fourier space.

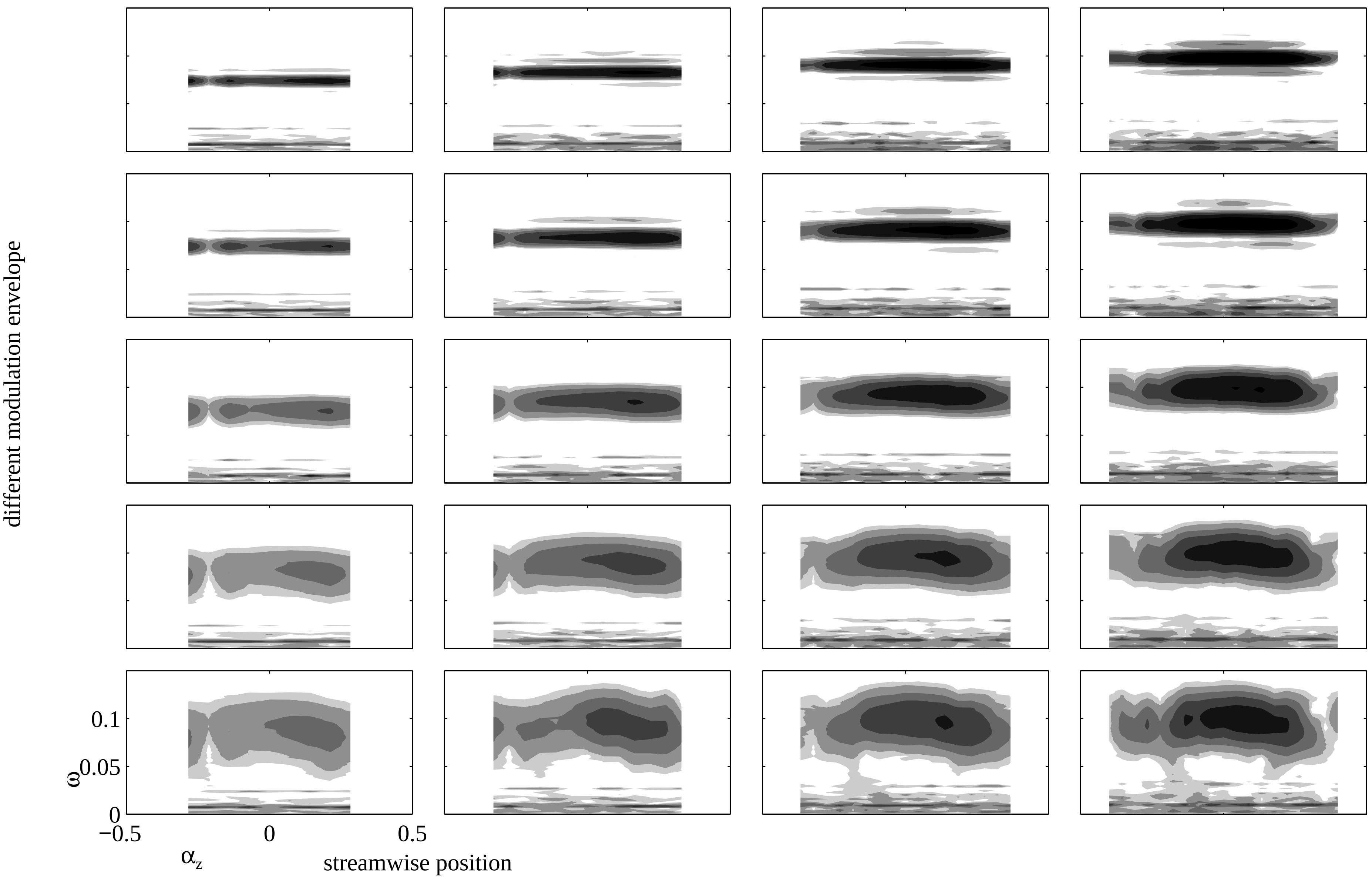

Figure 4: Evolution of modulated wavetrains in Fourier space. Station x=400mm to x=700mm

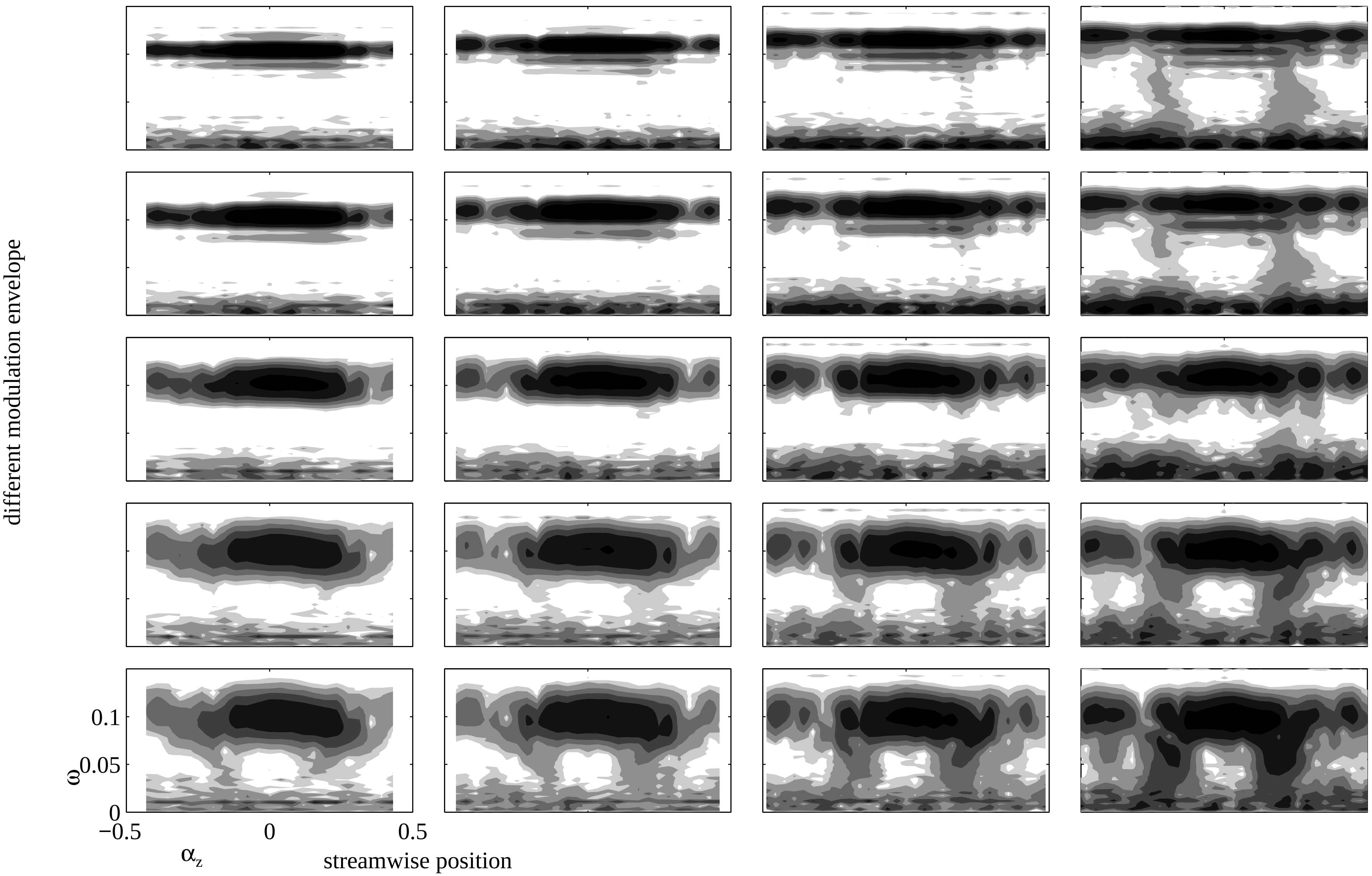

Figure 5: Evolution of modulated wavetrains in Fourier space. Station x=800mm to x=1100mm

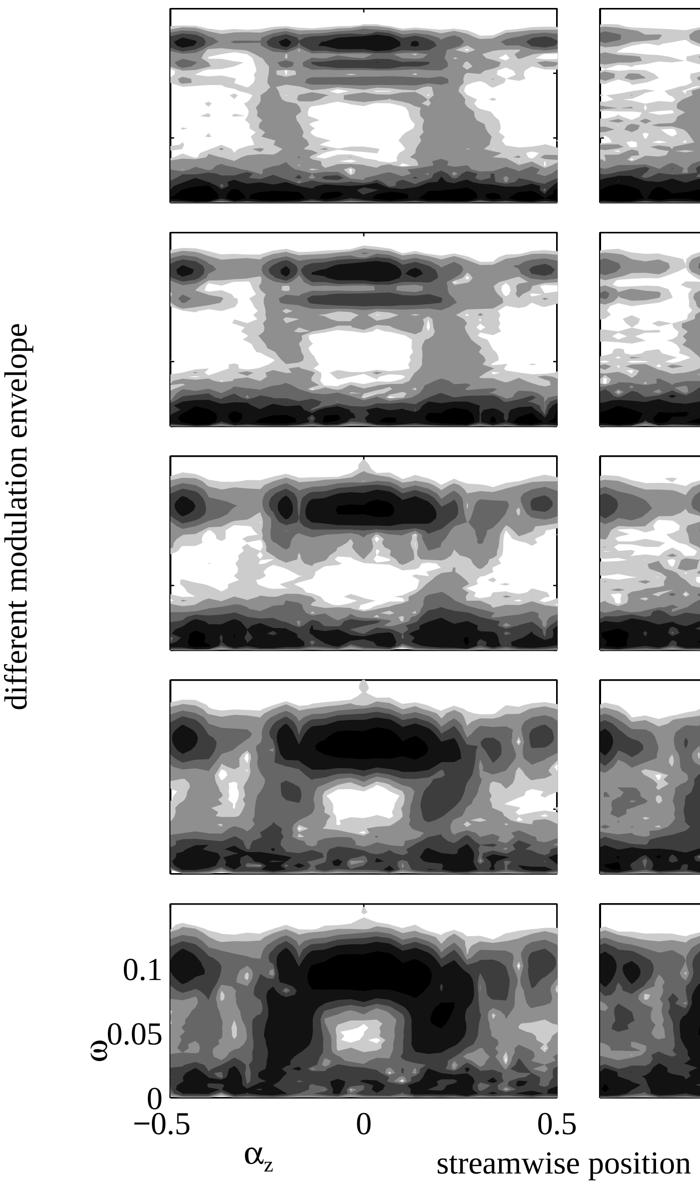

Figure 6: Evolution of modulated wavetrains in Fourier space. Station x=1200mm and x=1300mm