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Measurement of Boundary Layer Turbulent Transition Using an Acoustic Microphone Unit

Abstract

In this article the transition of a laminar boundary layer (BL) over a flat plate is characterized using an acoustic technique with a pitot probe linked to a microphone unit. The probe was traversed along a BL plate at a fixed wind tunnel flow velocity of 5.5 m/s. A spectral analysis of the acoustic fluctuations showed that this setup can estimate the streamwise location and length of the BL transition region, as well as the BL thickness, by using the intermittency similitude approach. Further work is required to quantify the uncertainty caused by signal attenuation within the data acquisition system.

I. Introduction

Understanding boundary layer (BL) transition remains a major challenge in many engineering applications [1]. A significant body of work has been done in this area experimentally, with typical measurement methods including hot-wire anemometry (HWA) [2], piezoelectric pressure transducers [3] and more recently optical [3] or acoustic methods [5]. Pitot-based or ‘in-flow’ methods have also been employed to measure the transition region, with a notable study completed by Dougherty and Fisher [6]. In this case, a pitot tube linked to a microphone, was traversed along a common research cone in a range of wind tunnels and in-flight, as part of a flow-field fidelity study on the BL characteristics in wind-tunnels or in-flight. In this simple arrangement, the pressure fluctuations and average signal, measured by the microphone, define the start and end of transition respectively. This method contrasts with high fidelity BL microphone-based methods, which seek detailed frequency and phase information during the measurement, thus requiring complex calibrations and signal processing methods [7].

Transition zone and the point determination presents many challenges, as reviewed by Narasimha [8] and Maeda [9], where they propose the intermittency approach. In this technical note, we demonstrate a simple acoustic pitot-based and intermittency method, to characterize the BL bypass

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transition [10] and BL thickness along a flat plate, which was used for teaching demonstration purposes. This method can equally be used to determine trip wire transition and is suited to a flat plat geometry, a key demonstration regime for teaching fluid mechanics to students. The paper demonstrates a proof-of-principle of the technique, with a simple wind tunnel configuration.

II.Experimental setup and data reduction methods

The system was tested in a 4' x 3' low-speed wind tunnel (Figure 1). Inside the working section, a smooth BL plate of length L = 1500mm, width W = 370mm, was mounted 150mm from the floor and the tunnel run in an open configuration, with a length of the working section, removed from the measurement area, to allow easy access for the test and to allow the *x-y-z* traverse to position the probe anywhere on the BL plate, from the surface to the free stream (Figure 2).

The velocity was monitored with a pitot probe with a nominal rms fluctuation of ±0.2m/s, although additional resonant fluctuations, due to the open working section, increased this to a rms velocity of ±0.37m/s with a resonant frequency of around 12Hz. This resonant fluctuation was subsequently filtered from the data.

To locate the transition, a Bruel and Kjaer (B&K) 2250 portable microphone logger was connected through a PVC flexible pipe, to a 2mm diameter brass tube, to create a total pressure pitot tube (see Figure 2). The B&K 2250 microphone unit has a frequency range of 6Hz – 20kHz, with a 48kHz sampling rate, a 24-bit data format and a dynamic range of 120dB, giving a pressure and velocity resolution of $2\text{x}10^{-5}$Pa and ±0.004 m/s at a total pressure of 20Pa. The microphone pitot tube was mounted onto an aluminium support and a streamliner structure. With this arrangement, the pitot tube could be moved to any point on the BL plate, to within ±1mm of the plate surface.

To determine the BL transition location, a series of measurements in x and y were made, about the plate centreline, with 70,000 samples per point as shown in Table 1. An approximate transition position was also verified before measurements with the microphone, by using a 2mm diameter pitot-based stethoscope arrangement, which was maneuvered over the BL plate manually. This enabled identification of the change from laminar to turbulent transition from the acoustic sound, to within a position in x from the leading edge of (x/L)±0.033 (±50mm) on the BL plate.

All microphone data was filtered to remove the resonant frequency originating from the open wind tunnel working section and converted into a dB power scale. As the resonant frequency was known to be around 12Hz, a Butterworth infinite impulse response (IIR), digital high pass filter was used. Filter settings were adjusted until the filtered signal power stabilized across the range of recorded samples. In this case, the final filter settings used a filter stopband frequency of 4Hz, a passband frequency of 8Hz, a stopband attenuation of 80 dB and passband ripple of 1dB.

Table 1 Wind tunnel measurement conditions at freestream velocity of $V_\infty = 5.5m/s$

Points	**Start (*x/L*),(*y/L*),(*z/L*)**	**End (*x/L*),(*y/L*),(*z/L*)**	**Notes**
1 - 121	0.158, 0.0033, 0	0.558, 0.0033, 0	$\Delta x/L$ = 0.0033 (5mm), fixed y, centreline in z, for transition point detection
122 - 125	0.158, 0.0033, 0	0.558, 0.0033, 0	Repeats at x/L = 0.158, x/L = 0.358, x/L = 0.558
126 - 145	0.158, 0.0033, 0	0.158, 0.0167, 0	$\Delta y/L$ = 6.67 x 10^{-4} (1mm), fixed x/L = 0.158, centreline in z, for boundary layer thickness measurement
126 - 165	0.358, 0.0033, 0	0.358, 0.0167, 0	$\Delta y/L$ = 6.67 x 10^{-4} (1mm), fixed x/L = 0.358, centreline in z, for boundary layer thickness measurement
126 - 165	0.558, 0.0030, 0	0.558, 0.0167, 0	$\Delta y/L$ = 6.67 x 10^{-4} (1mm), fixed x/L = 0.558, centreline in z, for boundary layer thickness measurement

To locate the transition region, the intermittency methods of Narasimha [8] and Maeda [9] were used and applied to the normalized power following the initial filtering. For intermittency similitude, the non-dimensional distance ξ and ξ_e were calculated using an onset position x_t, as defined by Narasimha [8]. The values of ξ and ξ_e corresponded to transition and BL thickness respectively. In the latter case, the 'edge' intermittency approach [9] was used to estimate the BL thickness during transition. Onset was estimated from spectrograms of the filtered signal, where visible bursts appeared over several

consecutive spectrograms. A series of typical spectrograms are shown in Figure 3, where the intermittency bursts become initially visible at $x/L = 0.178$ and are used to estimate onset position x_t. To characterize the extent of the transition region in ξ and ξ_e, the distance λ was specified based on intermittency levels γ of between $\gamma = 0.25 - 0.75$ (see Figure 4), where λ was adjusted to achieve the universality constant of intermittency of 0.412, from the gradient of the *ln* relationship, (see Narasimha [8] and Maeda [9]). Through λ and x_t, a transition region length and BL thickness could then be estimated (Figure 4). This universality in the data gives consistent similitude, in the transition region, and it's corresponding BL development.

III. Results and Discussion

Figure 5 shows the filtered and unfiltered intermittency data from the BL transverse in x. The transition region is clearly visible between $\xi^2 = 0$ (onset) and $\xi^2 = 3.8$, where the universality constant of intermittency of $m = 0.412$ is met (see line fit). Following this transition region, the universality behavior is lost, as clearly shown in the data scatter beyond $\xi^2 > 3.8$. Within the universality region, λ was estimated to be $(\lambda/L) = 0.1077$ with $(x_t/L) = 0.180$, thus defining the transition region. Full transition would therefore be expected beyond $x/L = 0.558$.

These two points defining the transition onset and full transition, have effective Reynolds numbers (Re_x) of 99,200 – 215,000 respectively. Narasimha [8] defines a relationship between onset Reynolds number Re_t and the Reynolds number Re_λ, based on λ. In this case at $Re_t \sim 10^5$, our $Re_\lambda \sim 60{,}000$ which is consistent with their findings. Their work also discusses the variability of the wind tunnel conditions on the transition behavior. In this case wind freestream turbulence levels were found to the <0.1%, based on hot wire anemometer measurements.

Boundary layer displacement thickness, δ, was estimated during transition at $(x/L) = 0.358$ (Figure 6), by applying the 'edge' intermittency methods of Maeda [9], analogous to Narasimha [8]. Here, $(\lambda_e/L) = 0.0078$ (11.7mm) to ensure that the universality constant of intermittency of m = 0.412. Given the initial height of the probe, this would correspond to $(\delta/L) = 0.0111$ (16.7mm) which is comparable to empirical estimates [1].

In summary, although this technique is straightforward, as needed for student exercises, it is intrusive and susceptible to signal attenuation uncertainties, yet it allows for the identification of transition initiation in both tripped and natural transition scenarios. This relies in the initial appearance of the intermittency bursts in the spectrogram (Figure 3). This interpretation is currently manual, but could be improved with machine learning methods, which suit current trends in data analysis. The end of transition also relies on intermittency similitude and signal attenuation may affect this. The distinct cut off in the intermittency data (Figures 5 & 6) though, shows a robust enough trend for student interpretation. Further work is needed to estimate the effect of these attenuation errors on the similitude.

IV.Conclusions

In this work, a pitot probe system has been combined with a Bruel and Kjaer (B&K) 2250 portable microphone logger, and intermittency data processing method, for teaching demonstrations. This system was used to detect the boundary layer transition region and displacement thickness during transition, with reasonable accuracy, but without the complexity of using a hot-wire anemometry. This measurement system has allowed detection of the transition region and BL thickness with an estimated resolution of (x/L) ±0.0033 (±5mm) and ($\Delta y/L$) = 6.67 x 10^{-4} (±1mm) respectively, at a Reynolds number range of Re_x = 99,200 – 215,000, for transition onset and full transition respectively, using a boundary layer flat plate with length L = 1500mm. Further work will refine this design, improve the spatial resolution, with a thinner pitot tube and further define signal attenuation errors. HWA measurements would be required to verify these improvements, to extend its application to BL research environments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported herein.

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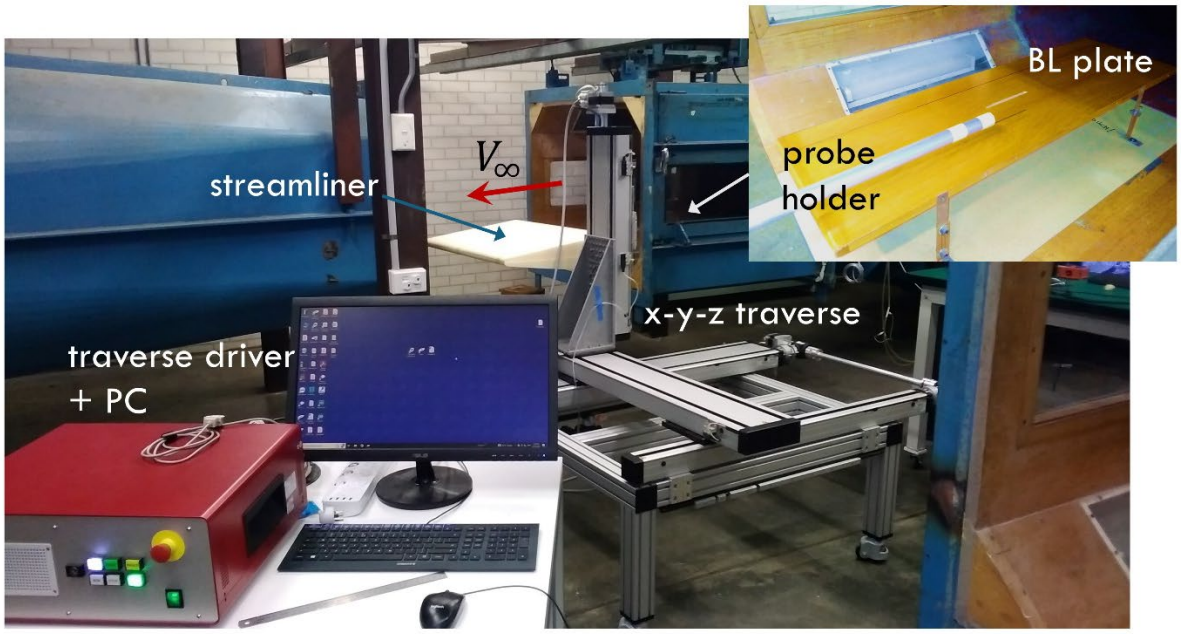


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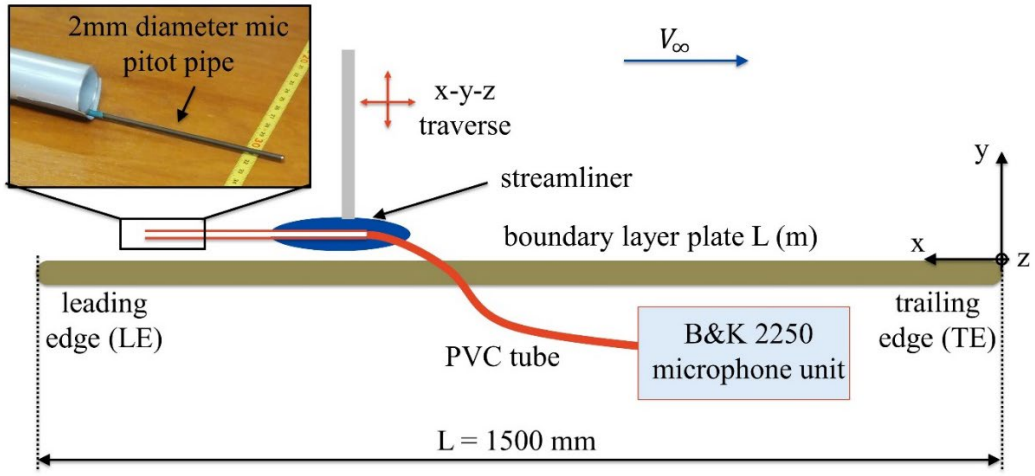


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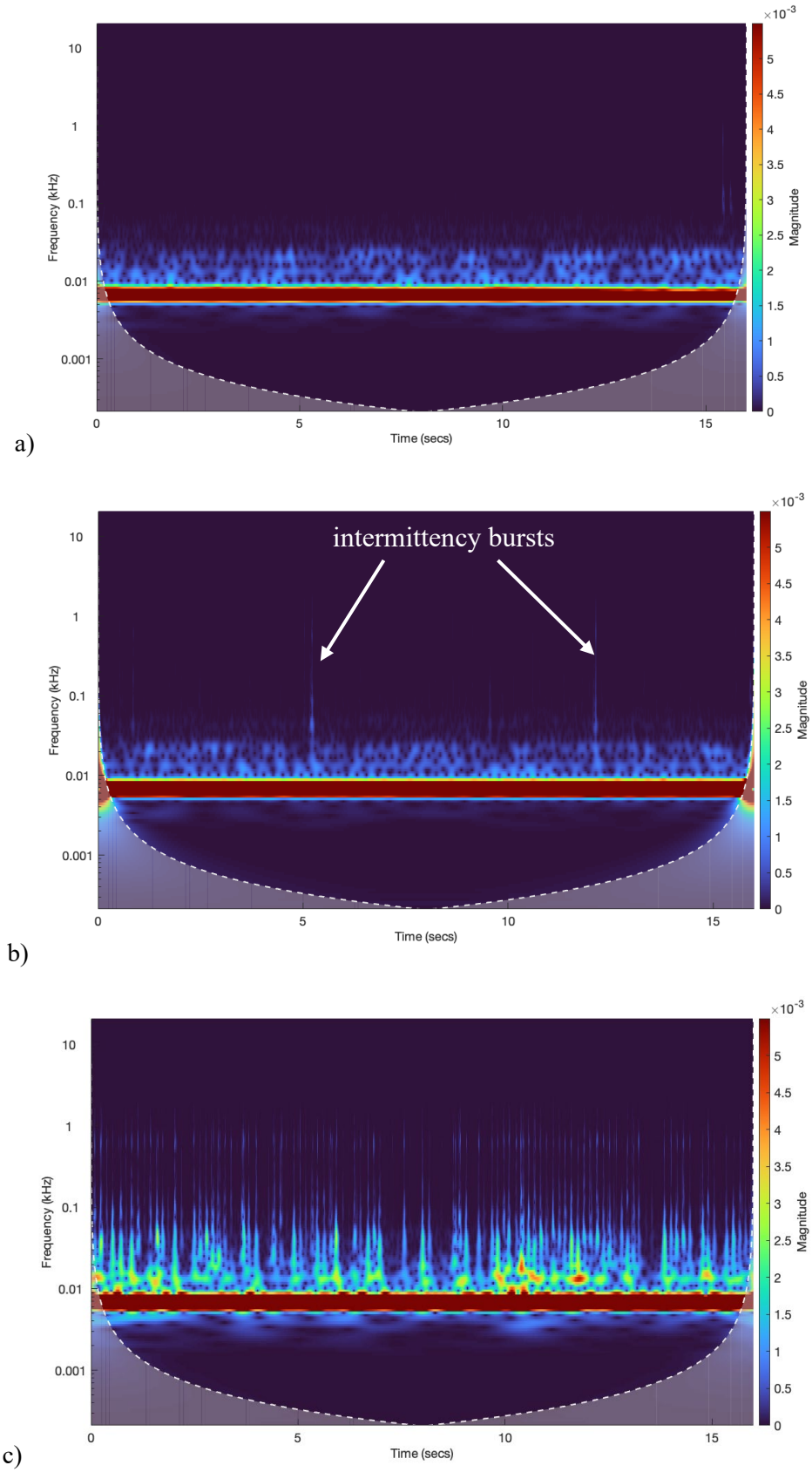


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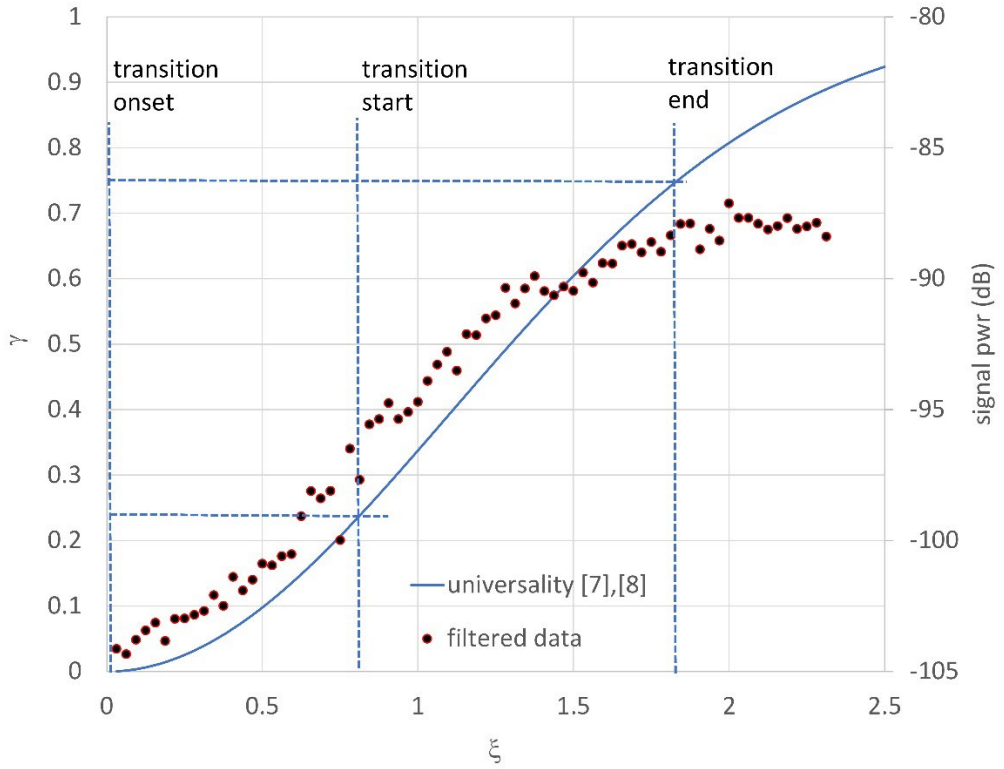


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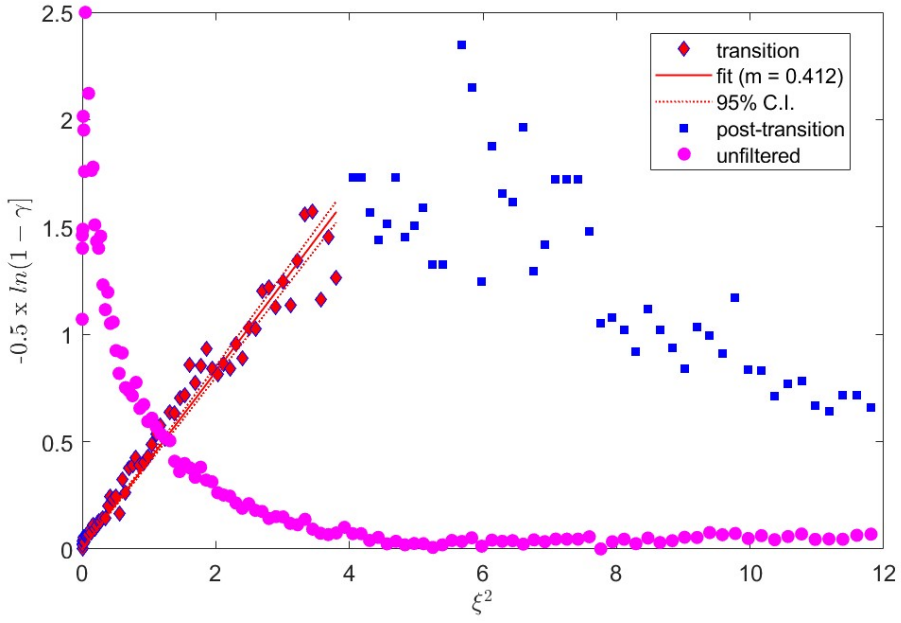


Figure 5 – Boundary layer intermittency x-profile ξ–γ, at (y/L) = 0.0033 from surface

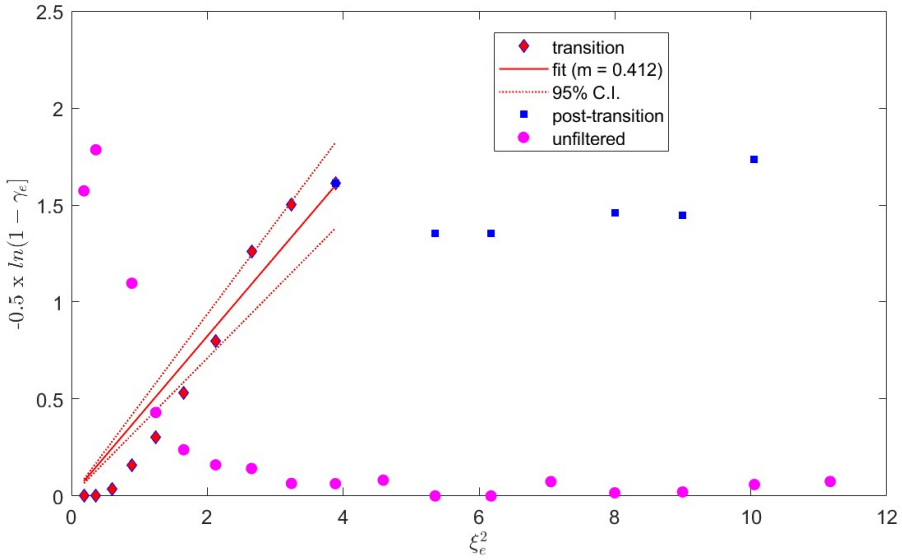


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