The four shear waves of transition to turbulence

Key Words

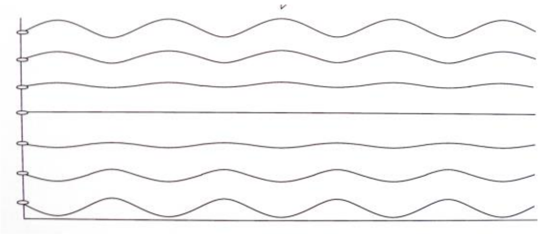
amplification, boundary layer flutter (BLF) waves, cavitation, compliant boundary (CB) waves, counter-rotating vortices, edge tones, flashes of turbulence, grabbing and releasing, head-over-heels vortices, H-tube, Hof-Delft, laminar flow, laminar freezing (interlocking), Nikuradse, shear, laminar membrane (LM) waves, Reynolds, simple harmonic (SH), SH cloud waves, SH sand waves, sound waves, streaming, transition to turbulence, turbulent spots, U-tube, velocity oscillations, vibrations, viscosity

Introduction

In 1941, simple harmonic (SH) velocity oscillations (which are not physical shear waves) proved the existence of SH oscillations in the laminae of the boundary layer [Schubauer and Skramstad 1941).

Discussion

During the dynamic phase of transition to turbulence along a smooth flat plate, SH ***velocity*** oscillations developed in boundary layer laminae [Schubauer and Skramstad (S and S), 1941]. Velocity oscillations are not, in themselves, shear waves, but are secondary manifestations of fluid shear oscillations in the compressible air laminae along the smooth flat boundary in a wind tunnel. Since transition to turbulence occurs similarly in flowing water, any explanation of the physics of boundary layer oscillations in wind tunnel air flow must be applicable to the shear waves of transition in water, which is incompressible.



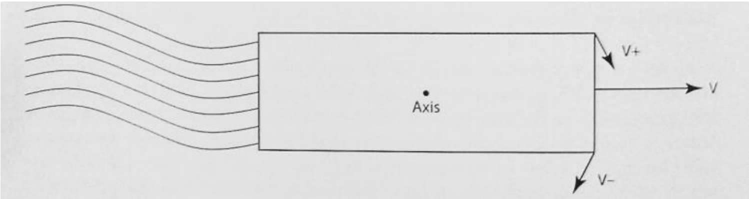
S and S velocity oscillations

In water flow along a smooth flat plate, the long crested simple harmonic (LCSH)-oscillation-containing lamina closest to the boundary must be associated with identical oscillations in the in the water lamina adjacent to it. Also, every other adjacent water lamina, layer upon layer, must conform exactly to these SHLC waves. Any variation in amplitude of adjacent water laminae (increase or decrease) would cause bands of compression (impossible with liquids) or decompression (impossible without cavitation). Therefore, all boundary layer water laminae – layer upon layer – must display identical in-phase sinusoidal SHLC waves, which will be termed boundary layer flutter (BLF) oscillations – the primary shear waves of transition.

S and S showed velocity oscillations gradually decreasing in amplitude as the distance from the boundary increased, reaching a plane of zero oscillations. As the distance from the baseline increased further (now above the zero oscillation baseline), the velocity oscillations reappeared, gradually increasing in amplitude, but 180 degrees out of phase (figure 1). S and S made an incorrect assumption that the fluid shear waves would conform to the contours of the simple harmonic (SH) velocity oscillations ("Simple Harmonics" 2015, p. 9).

To explain how this phase reversal will occur with velocity oscillations, but will not occur in the physical motion of the SHLC water oscillations, consider the physics involved in the creation of the out-of-phase velocity oscillations. Imagine a block of water that is ***one lamina in thickness*** and a length that is the distance between a wave crest and trough of a SHLC water oscillation (figure 2).

Starting with the block in a horizontal alignment, at the instant when viscosity-induced grabbing of transition starts along a flat plate, the anterior superior corner of the laminar block will arch downward and slightly forward, increasing the forward velocity slightly. Simultaneously, the anterior inferior corner will arch downward and slightly backwards, decreasing its velocity, 180 degrees out-of-phase



Simultaneously, the physical movements of equidistant points on the posterior end of the laminar block will describe simple harmonic sinusoidal paths as the SH grabbing and releasing continue – each identical in form, one upon the other. Thus, although the velocity oscillations are 180 degrees out of phase, the physical motions of each lamina –layer upon layer – must be in phase and identical in form – duplicating the form of all SHLC boundary layer oscillations (Hamilton 2015, Simple Harmonics, p. 10, Hamilton 2011, Order in Chaos, figure 7b, p. 19).

Consider that 1) an oscillation (vibration) of a mass in a fluid creates a sound wave, 2) an oscillation of a mass of fluid in that same fluid creates a sound wave and 3) simple harmonic oscillations in a mass of fluid, flowing in the boundary layer along a smooth flat plate during transition, create simple harmonic sound waves. Thus, SH oscillations (vibrations) of water flowing along a flat plate boundary must be associated with SH sound waves, generated in the boundary layer and reflected from the boundary transversely into the flow.

S and S showed SHLC oscillations gradually increasing in amplitude as distance from the boundary increased – until they erupted into turbulence. Logically, they showed certain frequencies of external SH sound harmonized with the boundary layer SH oscillations, amplifying them, precipitating turbulence at lower flow rates (i.e., lowering the critical Reynolds number).

The total mass of water in the wave crests of all the LCSH boundary layer oscillations of all laminae (flowing at their individual velocities) descends towards the boundary in the grabbing phase, striking toward the boundary simultaneously. In the rebound phase of the oscillation (vibration) the water mass in the troughs surges upwards, creating SH sound waves transverse to the boundary.

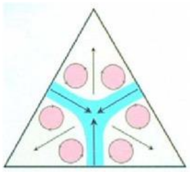
The "fluttering handbreadths" demonstration (Hamilton 2015: Simple Harmonics) shows how boundary layer flutter (BLF) oscillations form and flow with simple harmonic rhythm, creating SH transverse sound. These are the dominant shear waves of transition and cause the three other types of shear waves.

Feeding on the energy of the flow, the vibrational momentum of in-phase SH boundary layer flutter oscillations increases in intensity, accompanied by similar inter-related amplification of sound energy transverse to the boundary. As transition progresses, intense transverse oscillation of molecules through the horizontal laminae creates random focal areas of laminar freezing, abruptly shifting flow resistance to the high resistance of the boundary. This creates focal areas of head-over-heels vortices, as high velocity "frozen" fluid masses encounter spots of sudden braking along the boundary. Chunks of boundary layer wave fronts are torn off and roll downstream as "turbulent spots" (or Reynolds "flashes of turbulence" in cylinders). The many random turbulent spots emerging as generalized turbulence onsets, causes noisy turbulent flow.

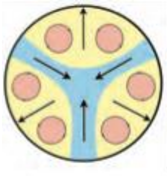
However, when an edge juts into the boundary layer normal to the flow during transition, all nascent turbulent spots are triggered to emerge in unison as stationary SHLC waves, yielding the SH sound of edge tones. In water flow in a shallow stream, a transverse linear deformity in the streambed similarly aligns all emerging turbulent spots, causing them to emerge simultaneously, creating SHLC stationary waves ("Simple Harmonics" 2015, p. 12).

In cylinder water flow, established "homogeneous" turbulence, with high energy transverse oscillation of molecules through frozen laminae allows organized transverse flow in cylinder sectors, each showing a repeating transverse flow pattern – a centripetal streaming flow from the boundary, flanked by a pair of counter-rotating vortices (Hof, Science 2004, Fitzgerald, Physics Today 2004). In 1930, Nikuradse found a similar transverse flow pattern in turbulence in tubes with triangular cross-sections.

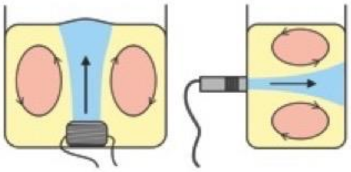
The transverse flow divisions are characteristic of flow generated by a coherent sound source, sonic, or ultrasonic (Hamilton 2015, Simple Harmonics) – each division having a centripetal central streaming flow from the boundary, flanked by a pair of similar but counter-rotating vortices. This pattern is consistent with the generation of SH sound by the SH BLF waves of transition.



Nikuradse 1930



Hof-Delf 1941



Sonic and ultrasonic coherent sound generators

U-tube and H-tube stationary compliant boundary (CB) shear waves and LCSH sand CB waves

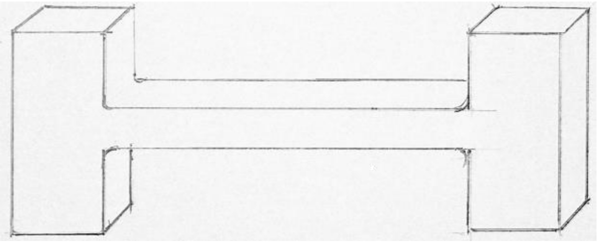
The Reynolds U-tube experiment shows water/carbon bi-sulfide shear waves as interface standing waves. The fluid shear creates interface CB waves in the carbon bi-sulfide compliant boundary, while similar fluid shear creates identical inter-digitating water CB standing waves. The physics is similar for the long crested simple harmonic (LCSH) waves occurring in the fluid shear between two adjacent air strata of different velocities; when the warmer air mass has higher moisture content than the colder stratum, LCSH interface standing wave clouds frequently appear ("Simple Harmonics" 2015, p.14, figure 16).

Inter-stratum SH cloud CB waves

Lingering contrail reveals inter-stratum CB waves

One might duplicate the physics of Reynolds LCSH fluid/fluid interface shear waves by modifying the Reynolds water/carbon bi-sulfide interface experiment, using a long flat clear plastic chamber (similar to the Reynolds U-tube sealed by corks), with reservoir compartments at each end (creating an H-tube) to replenish the fluids flowing bi-directionally along the water/carbon bisulfide shear interface. The interface should be at mid-height of the horizontal component of the tube.

An H-tube variant of the Reynolds U-tube experiment



Left reservoir Horizontal flat flow chamber Right reservoir

At a certain critical inclination, stationary LCSH interface waves should appear as the heavier carbon bi-sulfide flows towards the lower reservoir, while the water flows upwards into its reservoir. The water should form SHLC standing CB shear waves in the CS2 compliant boundary. The CS2 flowing downwards should form identical SHLC standing CB waves along the undersurface of the compliant water boundary.

In Thomas's glass bead experiment (DG Thomas, Science 1964), slowly sliding SHLC waves appear in a layer of tiny glass beads during transition in water flow in cylinders and persist in turbulence. Similarly, one might use only water flow (no CS2) and add a layer of sand* along the base of the flat flow section.[1] As water flows along the base of the flat tube, SHLC particulate waves should develop at a critical angle of inclination and these CB sand waves should slide slowly along the shiny flat surface. Lining the base of the tube with sand paper, and then adding a layer of sand, the SHLC sand waves should appear and will remain stationary, just like the sand waves in wind or water shear flows, proving an underlying standing wave nature.

Similarly, if air fills the upper half of the flat chamber and H-tube, with an air/water horizontal interface in the flat flow chamber, and a smooth layer of sand along the shiny plastic bottom, tilting should create LCSH sand CB waves in a layer of sand; the sand CB waves will slowly slide along the shiny plastic tube. Since all laminae conform to the shape of the sand waves as LM waves, there will be surface water waves that duplicate the form of the sand waves. Adding sandpaper along the flow chamber's base should arrest the sand waves and the similar surface waves, revealing their standing wave nature.

Similarly, when the layer of sand is in a shallow stream's streambed, the sand waves cannot slide on the underlying sand, and they will remain stationary. The sand CB waves conform to the standing wave paths along which boundary layer (BLF) oscillations flow – layer upon layer – each lamina flowing at a velocity that increases as its distance increases from the boundary.

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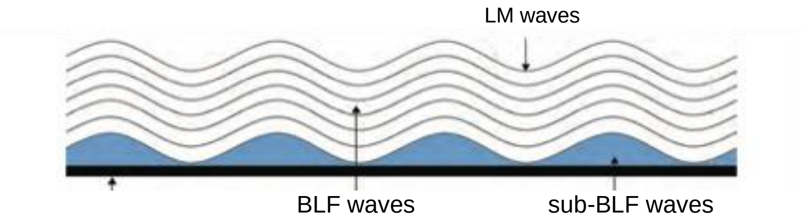
[1] * Sand is sifted and washed to achieve similarity in grain size and to prevent dirt from "muddying the waters."

Laminar membranes with SH standing waves

Of the shear waves of transition, laminar membrane waves are the most difficult to understand.

Each lamina has an individual velocity, which increases as the distance from the resistant boundary increases. As the velocity of a lamina increases, its rising momentum increases its resistance to deflection. This is similar to an increase in tension of a membrane increasing its resistance to deflection. Thus, a flowing lamina reacts like a membrane under tension. This emphasizes Morkovin's idea that "Like many other continuous systems, a shear layer is capable of natural oscillations around its mean state" (Morkovin MV: Transition from laminar to turbulent shear flow - a review of some recent advances in its understanding. Transactions of the American Society of Mechanical Engineers (1958); 80: pp. 1121-1128).

The simple harmonic long crested BLF waves create SHLC laminar membrane (LM) waves, which slide along the boundary as traveling waves, at a velocity much slower than the rate of flow. These LM waves, created by the dominant BLF waves, represent the paths along which BLF waves flow with flow velocities of each lamina determined by distance from the boundary.



Each LM wave path is similar for each lamina, layer upon layer, ***regardless of each lamina's velocity***. The standing wave nature is revealed when LM waves become stationary along a non-laminar compliant boundary, where CB waves form with the same contours as the LM waves.

In incompressible water flow along a rigid flat plate boundary, when the LM waves form, there must be sub-BLF oscillations under the LM wave crests. Just as one liquid lamina cannot diverge from or converge on any adjacent lamina without cavitation or compression, respectively, the lamina closest to the boundary cannot separate from the boundary under the wave crests of a boundary layer oscillation. The sub-BLF waves under the wave crests replace the CB waves that develop when the SHLC high pressure / low-pressure zones create the troughs and crests, respectively, in the compliant boundary.

Conclusions

Thus, there are four inter-related shear waves of transition: 1) BLF (boundary layer flutter) oscillations, which cause the others, 2) LM (laminar membrane waves, the paths traced by the BLF oscillations, 3) the CB (compliant boundary) waves, indented by the pressure zones of the LM waves, and 4) sub-BLF oscillations.

There are three types of shear waves along a smooth flat boundary: BLF oscillations, LM waves and sub-BLF oscillations.

There are three types of shear waves along compliant boundaries: BLF oscillations, LM waves and CB waves.

BLF oscillations, created in the boundary layer by viscosity, must be accompanied by SH sound waves. It is these sound waves, created on and reflected off the boundary, that result in laminar interlocking, shifting the flow resistance to the boundary, creating the phenomenon of turbulence.