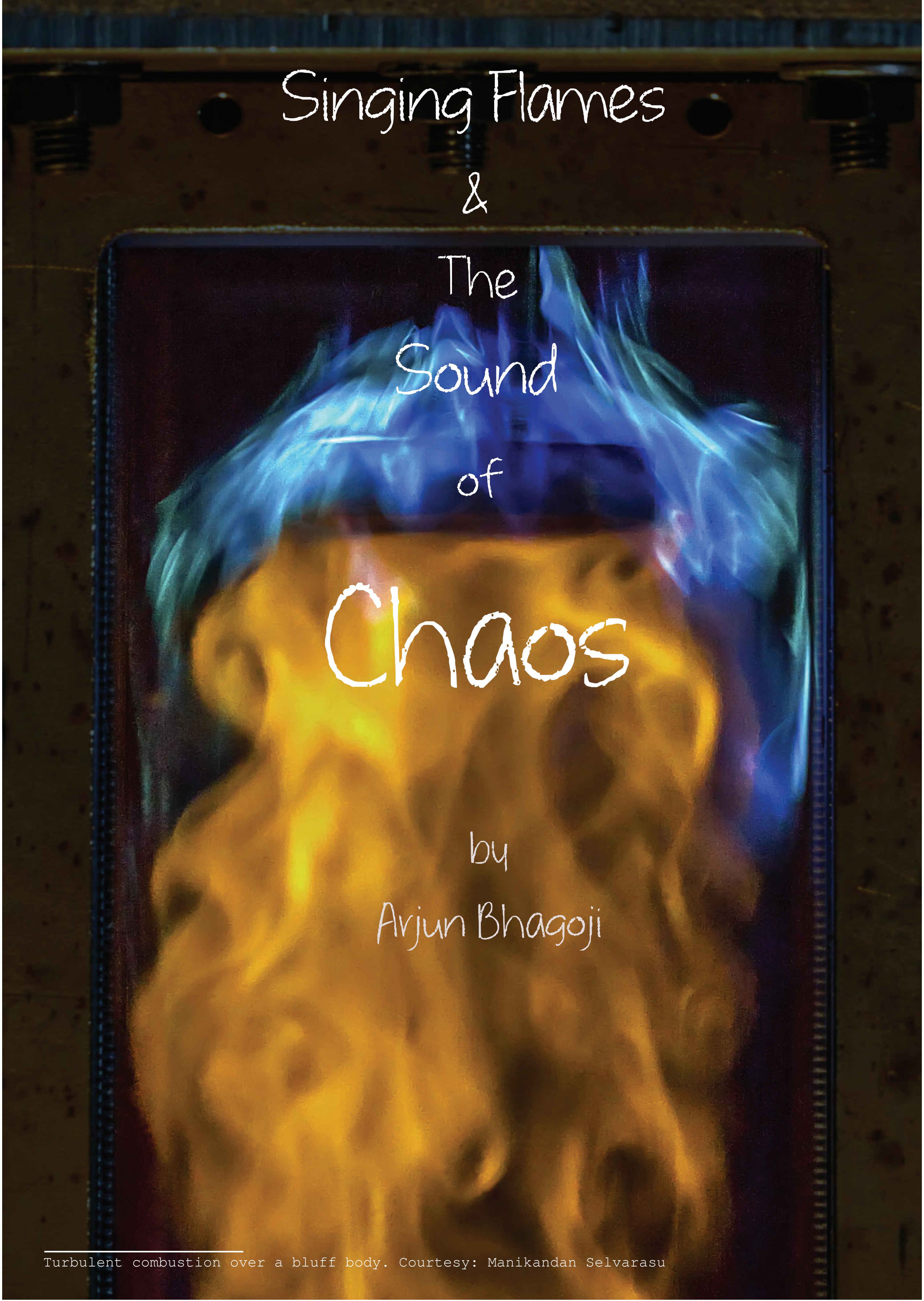


Singing Flames & The Sound of Chaos

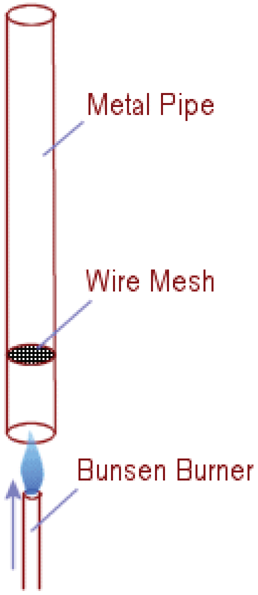
by

Arjun Bhagoji

Turbulent combustion over a bluff body. Courtesy: Manikandan Selvarasu

Chaos. It is, as Edward Lorenz so aptly defined it, “when the present determines the future, but the approximate present does not approximately determine the future.” A large number of systems that we encounter routinely such as radio circuits, weather and population models and even celestial systems of bodies exhibit chaotic behaviour. That is, these systems display a sensitive dependence on how they were set off in motion. In recent years, Professor R. I. Sujith of the Aerospace Engineering Department at IIT Madras has been using chaos theory and techniques involving nonlinear system analysis to effect what can be termed a revolution of sorts in the study of thermoacoustic systems.

Acoustic waves, commonly known as sound waves, have the distinct feature that the back and forth motion of packets of air that produces the sound happens along the same direction as the wave motion. The oscillation of air packets creates variations in pressure along the path of the wave. The sound produced by such a varying pressure field can be amplified on interaction with local inhomogeneities in temperature and density. A simple example is a Rjike tube, which in its basic form consists of a source of unsteady heat release (such as a flame) that produces sound inside a confining chamber that allows for the transmission and reflection of generated sound waves. Aircraft engines, gas turbines and industrial burners are all examples of such ‘thermoacoustic’ systems.



A Rjike tube. Courtesy: Sudhir P, CC-BY-SA-3.0

Sudden excitation of large-amplitude pressure oscillations is a routine problem in thermoacoustic systems. Fluctuations in the flame produce sound waves that get reflected back at the boundaries of the confinement towards the flame location, resulting in further flame fluctuations that create sound waves, and so on. Thus, the conversion of unsteady heat release rate to sound creates a positive feedback and an increase in the amplitude of pressure oscillations; this phenomenon is termed thermoacoustic instability. This is similar to the feedback effect observed when we place a microphone near a speaker, which very quickly leads to a loud, shrieking noise. Thermoacoustic oscillations can, at times, be violent enough to cause wear and tear and sometimes even complete breakage of machine parts.

Thermoacoustic instabilities are hence a huge problem for the propulsion and power-generation industries. In gas turbines used for power production, the instability is typically detected using pressure transducers after it has already occurred. Once an instability is detected, the turbines have to be shut down and restarted, which easily takes about an hour. Contracts between the turbine manufacturers and the power companies often require the manufacturers to bear the cost of such shutdowns.

Thermoacoustic instabilities result in annual losses of billions of dollars for the power industry.

The situation is more critical when such instabilities arise in an aircraft’s or a rocket’s engine where the option to shut down the engine in mid-air is non-existent and severe vibrations or breakage of the engine can prove to be fatal. For such engines, extensive tests have to be run on-ground. However, a substantial number of these engines, especially for rockets, gets destroyed while testing.

Now, the key questions are: can we predict the onset of instability and prevent damage to engines and gas turbines? Also, is there a way to study these instabilities appropriately in a laboratory environment and apply the knowledge to engine and gas turbine design? Prof. Sujith has been attempting to answer these questions since he came back to his alma mater in 1995. In a small building behind the Aerospace Department, Prof. Sujith and his students have tackled, and to a large extent

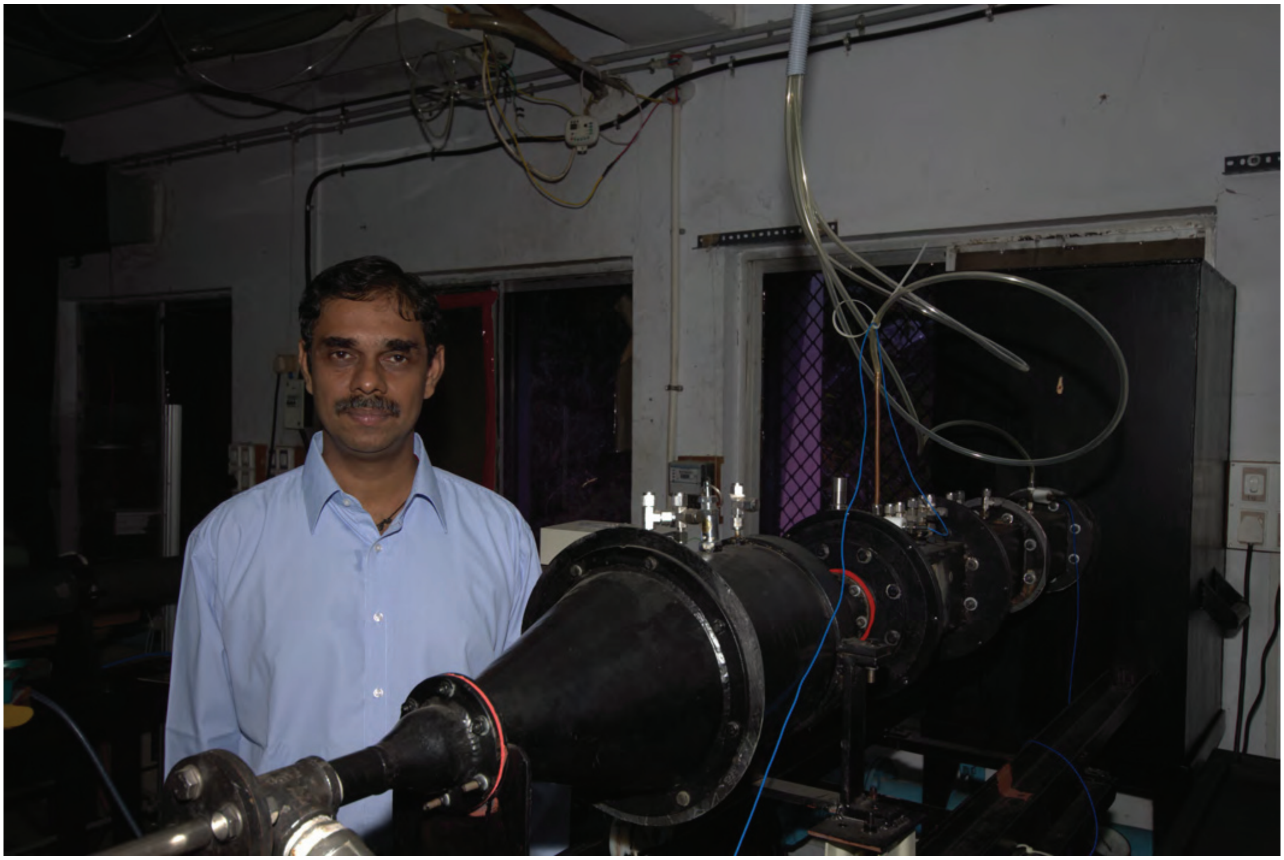
Prof. Sujith's group at IIT Madras. Courtesy: Luca Agrati

answered, fundamental questions about thermoacoustic instabilities with equipment that they have devised themselves for the most part.

A few years back, Prof. Sujith was studying acoustically enhanced waste incineration as well as basic problems on sound propagation. Waste incineration is one among a few scenarios where thermoacoustic instabilities are useful. This is because when combustors make a lot of sound, it helps mix and incinerate the waste efficiently. Prof. Sujith wanted to excite low frequency sound to improve incineration; however, the combustor that he used produced sound only at high frequencies, and was stable at low frequencies. To circumvent this difficulty, he devised a strategy wherein the combustor was started at high frequencies and thereafter the flame-holder position was quickly adjusted to get the combustor to work at low frequencies.

The effectiveness of this trick fascinated Prof. Sujith and he set out to find out why his method worked. What he discovered has led to a paradigm shift in the way thermoacoustic instabilities are viewed and analyzed. Traditionally, a linear stability analysis of eigenmodes was used to diagnose the stability of the system. An eigenmode is a vibrational mode of an oscillatory system, and in this case, the oscillations are in the air packets that vibrate in the engine. When the eigenmodes of the system are orthogonal (which in this context implies that vibrations at different frequencies do not interfere with each other), the stability of the individual eigenmodes determine the stability of the system. Prof. Sujith, working with Koushik Balasubramanian, then a Dual Degree Masters student, found that for thermoacoustic systems, eigenmodes are not orthogonal and can therefore interact with each other. The trick earlier with the flame worked precisely because of such an interaction between the modes at low and high frequencies.

The concept of instability due to non-orthogonal eigenmodes can be understood visually, if we regard the eigenmodes of the system as vectors in 2D space. Then, if the eigenvectors are orthogonal (that is, at right angles), as either or both are reduced, the resultant sum of the two vectors also reduces in magnitude. On the other hand, if the two vectors are not orthogonal, then decreas-

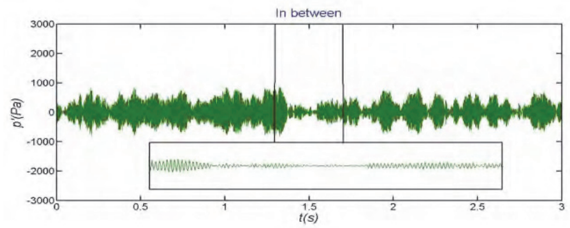


Prof. Sujith with the turbulent combustion chamber built by Gireeshkumaran Thampi, a current Ph.D student in the lab. Courtesy: Luca Agrati

ing one can momentarily cause the resultant to increase. In the case of a thermoacoustic system, this temporary increase can destabilize the system by kick-starting a nonlinear instability. Hence, the traditional controllers for thermoacoustic systems that rely on linear stability analysis and the assumption of orthogonality are bound to fail. This was the first major step that Prof. Sujith took in changing the way thermoacoustic instabilities are viewed, bringing the thermoacoustic community's attention to the group working at IIT Madras.

Another traditional assumption was that large-amplitude pressure oscillations, termed limit cycles, result when the acoustic power generated by the flame matches the losses in the system. These limit cycles can actually be visualized as closed contours in the phase space of the system, which is simply a plot of the variation of a system parameter as a function of other system parameters. For thermoacoustic systems, the measured pressure signal near the confined flame and time-delayed versions of the same pressure signal can be used as the relevant system parameters to create the phase space, thanks to a mathematical theorem known as Takens' delay embedding theorem.

Lipika Kabiraj, a former Ph.D student of Prof. Sujith's, conducted experiments on a ducted flame to study the transition to limit cycle pressure oscillations upon changing the position of the flame. The flow through the duct was kept laminar, which simply means that the fluid or gas packets move in parallel layers, with no disruption between the layers. One can contrast such a flow pattern with a turbulent flow where there is rapid and thorough mixing between the layers. She observed that the thermoacoustic instability is not made up of just single frequency oscillations, but also contains several interesting non-linear dynamical states such as quasi-periodicity, intermittency and chaos. This finding led Prof. Sujith and his group to realize that thermoacoustic phenomena are essentially nonlinear and therefore have to be studied from the point of view of dynamical systems theory. The obvious logical next step was to look for such states in a turbulent thermoacoustic system, which is the flow situation one is more likely to encounter in engines deployed in the field.



Intermittent bursts occurring prior to the onset of thermoacoustic instability. Courtesy: Vineeth Nair and R. I. Sujith

When a combustion chamber with a turbulent flow passing through it is mechanically stable; that is, without vibrations, the interaction of the flame, the flowfield and the acoustics results in a muted hum, a sound that is referred to as combustion noise. Noise in a system, by definition, is random behaviour that cannot be accounted for or written down in terms of deterministic equations. Distinguishing between chaos and random behaviour is notoriously difficult in practice. What Prof. Sujith and one of his former Ph.D. students Vineeth Nair found is that the so-called 'combustion noise' was a result of chaotic dynamics. They observed that when the proportion of fuel that burns with a fixed amount of air is altered, large-amplitude pressure fluctuations are created in the combustion chamber. This sudden transition and its critical sensitivity on continuously varying system parameters like the amount of air used for burning makes prediction of an instability notoriously difficult and its prevention next to impossible, especially in systems that require immediate control action such as a military aircraft engine.

So, the group began looking for precursors to instability, that would allow an engineer in the field to take precautionary measures and sustain the combustor in a state of stable operation. As they were performing the experiments in their lab at IIT Madras, using earmuffs against the deafening sound of the combustors, Prof. Sujith noticed that the students performing the experiment were able to intuitively predict when the system was about to become unstable. After listening to the sound produced by the combustors for a few experiments, he realized that even he could predict the onset of instability. There was a distinctive burst sound that occurred every now and then, in seemingly no partuicular pattern just before the instability. When the operating conditions were varied in a controlled manner towards instability, the combustor was first stable, where it produced the low humming sound. Then, as instability is approached, there were the bursts, until eventually the combustor entered regimes of unstable operation, as indicated by a sharp loud tone.

On analyzing the data from the time just before the instability, they realised that the bursts correspond to a type of behaviour known as intermittency in the language of dynamical system theory. Thus, the old paradigm for instability in combustors, which was simply stable → unstable was replaced by a new one, chaos → intermittency → periodic oscillations.

In technical jargon, a chaotic time signal is a fractal in time; that is, it has patterns that appear the same at different time scales. This property of fractal signals is known as self-similarity. Since the combustor dynamics was chaotic for mechanically stable operation, Prof. Sujith and Vineeth looked for a fractal structure in the data sets. However, the complexity of the system led to the surprising result that the pressure fluctuations of different amplitudes scale differently with time; that is, there is a spectrum of self-similar patterns, a feature known as multifractality, that can be observed by scaling the data differently. Thus, they realized that, measurements from the combustor have a rich multifractal structure at stable operation which finally collapses to a single point at instability, indicating that there is now only a single dominant time scale of relevance to the system. The good news is that this collapse happens in a gradual manner, unlike the pressure amplitudes that rise abruptly only at instability. The loss of multifractality thus allows one to predict an instability before it occurs, giving adequate time to deploy strategies to make the combustor operation stable, thereby avoiding the regime of instability altogether.

Prof. Sujith and his group are now working towards an understanding of the physics underlying the observed intermittent behavior. They are also exploring the occurrence of intermittent bursts in other fluid-based systems such as aeroelastic, aeroacoustic and even biological systems. They are looking for connections between all these systems, to see if there are some universal underlying principles. The type of investigations Prof. Sujith's group has carried out using simple, yet insightful experiments and the immense impact their work has had on the power industry can serve as an inspiration for researchers around the country ■