A NEW EXPERIMENTAL TECHNIQUE TO DETECT INSTANTANEOUS STAGNATION AND SEPARATION POINTS ON PITCHING CIRCULAR CYLINDERS

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Abstract

A new experimental technique, to obtain the spatial movement characteristics of the critical aerodynamic flow features such as stagnation and separation points on pitching circular cylinders, is demonstrated through wind tunnel experiments. The cylinders were instrumented with multi-element surface film sensors and tested using a bank of constant voltage anemometers (CVA) and multi-channel data acquisition, analysis, and instrumentation system (DAISy). The dynamics of the stagnation point location (SPL) and separation point location (SePL) were detected in real time and confirmed from the presence of an opposing trend in the mean voltage output from the sensors located across these critical points. The spectral analysis of the surface flow signatures distinctly showed the flow and model oscillation and dither frequencies. The cylinder nodel was subjected to pitch oscillating frequencies of 2 to 7 Hz.

Introduction

Most of the fluid-mechanical components used in aircraft as well as in industry, encounter unsteady flow situations, either caused by the flow or by the component interacting with the flow. Research and development studies involving unsteady flow diagnostics provide the insight necessary to improve the design, performance, handling, and safety of such components. Temporal and spatial complexity are inherent in unsteady flows and hence measurements and analysis techniques are challenging. Circular cylinders are geometrically simple and are excellent test models to verify new techniques and to understand complex flow phenomena.

Flow around a circular cylinder is a classical fluid mechanics problem which has been extensively studied for more than a century providing an abundance of details on fluid flow phenomena. Major portion of the studies were related to steady-state flows with a few of them on unsteady flows[1]. Recent investigations on unsteady flows associated with cylinders mainly focus on the vortex shedding characteristics in the near wake of flow past the cylinder. Numerical studies on impulsively started rotating and translating cylinders[2] and oscillating cylinders in horizontal direction[3], and experimental studies on steady and pulsed flows[4] are some examples. Extensive research studies are underway on unsteady aerodynamic problems associated with aircraft dynamics[5-7]. There is abundant literature available on this subject which is not quoted extensively in this paper. The emphasis of this paper is to describe a new experimental technique to obtain SPL and SePL in real time and present some typical results obtained from experiments conducted on simple pitching circular cylinder which can be easily extended to unsteady aircraft dynamics research.

Conventional pressure or force measurements, which are generally used in unsteady aerodynamics, are associated with elaborate instrumentation and limited frequency response. Some surface embedded hot-wire[5] and heat transfer gage measurements[4] are reported to indicate the usefulness of time resolved heat

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transfer measurements in unsteady environment. Present study employs non-intrusive surface flow measurements with hot-film sensors, constant voltage anemometers and associated instrumentation, and flow diagnostics. The instantaneous locations and the spatial movement of the stagnation and separation points on pitching cylinders at different (frequency, amplitude, and freestream velocity) test conditions were obtained. This new technical approach which is verified on pitching cylinders, is expected to set a precursor in unsteady flow measurements. The experimental set up including details of the model dimensions, oscillating mechanism, sensors, instrumentation, data acquisition, and flow diagnostics system are described below, followed by a discussion of the main results and conclusions.

Experimental Program

Experiments were conducted in open circuit wind tunnels of 2 in. x 2 in. and 4 in. x 6 in. test sections, at freestream unit Reynolds numbers of 7×10^5 to 8×10 and 4.8×10^5 per foot, respectively. Multi-element surface hot-film sensors were attached to the test models and used in conjunction with a bank of constant voltage anemometers (CVA) and multi-channel data acquisition, analysis and instrumentation system (DAISy) to obtain the stagnation and separation points from simultaneously acquired signals from the surface hot-film sensors.

Model and Instrumentation

Three circular cylinders of 0.32, 0.25, and 0.5 inch diameters were tested and will henceforth be referred to as model A, B, and C, respectively. The surface films were made of nickel sensors with copper leads and had a nominal resistance of 7 to 12 ohms. The width and length of the sensors were 4 and 57 mils, respectively. The instrumentation system which included sensor, CVA, and data acquisition system had a frequency response of 20 kHz. An oscillating mechanism consisting of a servo motor and associated linkage was connected to the cylinder at the center to obtain pure sinusoidal pitching motion (Figure 1). The servo motor was controlled by a function generator and a DC power supply. A potentiometer connected to the model was calibrated and used to obtain the position of the model at any given instant of time. The models were mounted on two sealed bearings and fixed to the tunnel test section such that the bearing surface was flush with the inside wall of the test section. The signal from the potentiometer and from the sensors were acquired simultaneously through channel 1 and the remaining 15 channels (2-16), respectively.

Results and Discussions

Present results are based on the measurement of convective heat transfer obtained from the sensors located on the surface of the cylinder. The shear stress at stagnation and separation points are a minimum and hence the local temperature at these points attains a maximum value due to minimum convective heat transfer. A resistive sensor located at these points will have greater resistance than the neighboring sensors and will result in a minimum output voltage when operated in the constant voltage mode. This method of determining the stagnation point has been reported in Ref. 8. This principle has been used in the present study to identify the stagnation as well as separation points during the dynamic condition of the model. These results are confirmed using the opposing trend present in the mean signal voltage across the SPL and SePL. In addition, the signals also captured the model oscillation frequency.

Results from Model A

A few instantaneous positions of the pitching cylinder are shown in Figure 2. The inner disk represents the cylinder and has the sensors numbered from 2 to 16 and the outer disk is a protractor. At any instant of time during the pitching motion of the cylinder (center disk), the angle between the reference sensor (sensor 8), and the flow direction is designated as the angle-of-attack.

Signals were acquired at a sampling frequency of 4,000 Hz (anti-aliasing filter set at 1,000 Hz) and for period of about 1 to 2 seconds. Figure 3 shows a typical dynamic (mean and fluctuating) signal (DC + AC) from sensors 2-15 located on the surface of the circular cylinder at 10° intervals. The time series in this figure is normalized and stacked to bring out the movement of SPL and SePL in a compact form. The amplitude of pitching oscillation was about ± 30°. The variation in the voltage from various sensors provides a vivid picture of the dynamics of the SPL and SePL. The locus of SPL with time is clearly indicated by the travel of the minimum voltage with time. For example, at time T_6, the sensor 6 is located at the stagnation point and the sensor 16 is close to separation. The boundary layer is laminar on either side of the stagnation point. The clear movement of the stagnation point from one sensor to the next is seen by the shift in the minima (shown by large dots on each signal trace). Thus at time T_6, the sensor 6 is at the stagnation point, at time T_9 the sensor 9 is at the stagnation point, and so on. At time T_{12} the pitching motion changes direction. Thus, the sensor 12 traverses the stagnation point in quick succession. The sensors 11 to 6 pass through the stagnation point in the reverse order compared to the first half cycle. The locus of the stagnation point locations is shown by dashed line.

Similarly, the separation point travel is indicated by the second minima in the voltage signal. For a given sensor and operating condition, the minimum voltage at the separation point was always lower than the minimum voltage observed at the stagnation point. Whereas, the boundary-layer was laminar on either side of the stagnation point, in the case of the separation point, the flow was laminar upstream of separation and turbulent downstream. It has been also observed in earlier studies that the state of the boundary layer (laminar, transitional, or turbulent) is practically the same on either side of the stagnation point, whereas the boundary-layer states are significantly different on either side of the separation point. While the picture shown in Figure 3 has been limited to a period of about one second (one cycle), the movement of all critical features were continuously observed in real time during wind tunnel tests.

Results from Model B and C

A larger cylinder (Model B, 2.5" diameter) was used to increase the resolution of angular spacing of sensor elements from 10° (model A) to 4.6°. For this cylinder, when the pitch amplitude was about ±15°, only the sensors 4-12 would cross the stagnation point. The cylinder was oscillating about sensor 8. The sensor element 8 can be considered the 'mean' stagnation point. Thus, we observe a dither frequency clearly present in signals from the sensor element 8 (Figure 4). In fact, all of the sensors within the segment of ±15° exhibit the presence of the dither since the stagnation point cuts across these sensor elements twice in a given cycle. However, the interval corresponding to each sensor passing through the SPL will be different and will depend on its location. It is to be noted that the half cycle amplitudes are equal (Figure 4) for sensor 8 oscillating equally about the freestream flow direction. Sensors 2-3 and 13-16 have a single predominant frequency corresponding to the frequency of oscillations of the model.

Figure 5 (a) shows a typical time series from a few sensors (8 to 12) corresponding to an instant when sensor 10 comes to the stagnation location exhibiting an opposing trend in the mean voltage between sensors 9 and 11 with a dither frequency present in signals from sensor 10 (The signals from 2 to 7 and 9 to 16 were showing the same trend, respectively). The phase correlation also exhibits 180-degree phase shift across SPL (Figure 5 (b)). The other instants when the stagnation occurs at sensors 8 and 6 are shown in Figure 6. The autospectra (Figure 7) of all of the signals indicated the dominant frequency corresponding to the model pitching frequency as well as the dither frequency associated with the sensor crossing the SPL due to model pitching. It should be noted that both of these frequencies are due to the pitching motion of the model.

Figure 8 shows the frequency spectra obtained from the hot-film sensors for different model oscillating frequencies V_{f1} to V_{f4} (2 to 7 Hz), and for a defined freestream velocity. The autospectra distinctly shows the model oscillating frequencies and the stagnation flow oscillation frequency corresponding to vortex shedding. The hot-film sensors see the model oscillation as the model boundary motion in relation to the fluid flow. Thus, the model and the flow oscillation frequencies are picked up by the hot-film sensors. It can also be seen from the figure that the stagnation flow oscillation frequency is not affected by the model boundary oscillation.

In addition to the above results, we made new observations of the flow dynamics which appears to have great significance to unsteady-flow diagnostics. Consider the enlarged view of the voltage signals for a short duration of time (Figure 9). The signals are arranged such that the minimum DC values are same. The minimum voltage from each sensor element corresponded to the location of the stagnation points and is indicated in the figure by large dots. At time t = 0.931 seconds, the sensor 10 is located at the stagnation point, at time t = 0.95 seconds, the sensor element 9 is located at the stagnation point, and so on. As the sensor element approaches the stagnation point, the signal amplitude from that sensor element decreases, reaching a minimum at the instant it is located exactly at the stagnation point. As the sensor element recedes from the stagnation point, the signal amplitude begins to increase. The instant of time when two signals cross each other is an indication that at that instant the stagnation point was located between them. Thus, signals from sensors 9 and 10 cross at $t \approx 0.942$ seconds. Although no sensor element is present exactly at the stagnation point at this instant of time, knowing the frequency of oscillations it is possible to compute the exact location corresponding to this instant of time. The typical delay in the aerodynamic movement can be seen from Figure 9. A phase reversal signature in the AC component of the signal is also seen at the SPL and this PRS is related to the stagnation point frequency due to the vortex shedding.

Conclusions

Wind-tunnel experiments were conducted on cylinders of different diameters, to detect the stagnation and separation points during the pitching motion of these models.

- For the first time, the dynamics of stagnation point location (SPL) and separation point location (SePL) were detected in real time during the pitching motion of cylinder models from the mean and fluctuating (DC and AC) surface flow signatures. The local minima in DC values of the signals corresponded to the location of stagnation and separation points in steady as well as pitching conditions.
- An opposing trend in the mean voltage variation was found across SPL and SePL in dynamic conditions. The phase correlation between these signals showed a 180° phase shift. It should be noted that this phase shift is different from the PRS characteristics observed across the stagnation point in steady state model conditions. These observations have significant relevance to unsteady aerodynamic applications.
- The mean voltage variation from two consecutive sensors in motion crossed each other when the stagnation or separation point were in between them. This observation indicates that we can develop a powerful tool to obtain the SPL and SePL at all instants of time by interpolation using only a few sensors, thereby increasing the resolution substantially.

Acknowledgment

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References

[1]P. W. Bearman and J. M. R. Graham, "Vortex Shedding from Bluff Bodies in Oscillatory Flow: A Report on Euromech 119," J. Fluid. Mech., Vol. 99, part 2, 1980.

[2]Chien-Cheng Chang and Ruey-Ling Chern, "Vortex Shedding from Impulsively Started and Translating Circular Cylinder," J. Fluid. Mech., Vol. 233, 1991.

[3]Mittal and Tezduyar, "A Finite Element Study of Incompressible Flows Past Oscillating Cylinders and Aerofoils," International J. for Numerical Methods in Fluids, Vol. 15, 1992.

[4]D. P. Tellinois, M. Gundappa, and T. E. Diller, "On the Organization of Flow and Heat Transfer in the Near Wake of a Circular Cylinder in Steady and Pulsed Flow," Transactions of the ASME, 1992.

[5]Lawrence W. Carr, Kenneth W. McAlister, and William J. McCroskey, "Analysis of the Development of Dynamic Stall Based on Oscillating Airfoil Experiments," NASA TN D-8382, 1977.

[6]Jay M. Brandon and Gautham H. Shah, "Unsteady Aerodynamic Characteristics of a Fighter Model Undergoing Large-Amplitude Pitching Motions at High Angles of Attack," AIAA paper No. 0309, Reno, Nevada, 1990.

[7]Mukund Acharya and Metwally H. Metwally, "Unsteady Pressure Field and Vorticity Production Over a Pitching Airfoil," AIAA Journal, Vol. 30, No. 2, 1992.

[8]S. M. Mangalam, S. Venkateswaran, and S. S. Korategere, "Measurement of Surface Flow Features at the Stagnation Region of a Swept Cylinder," AIAA 94-0731, AIAA 32nd Aerospace Sciences Meeting, Reno, Nevada, January 1994.

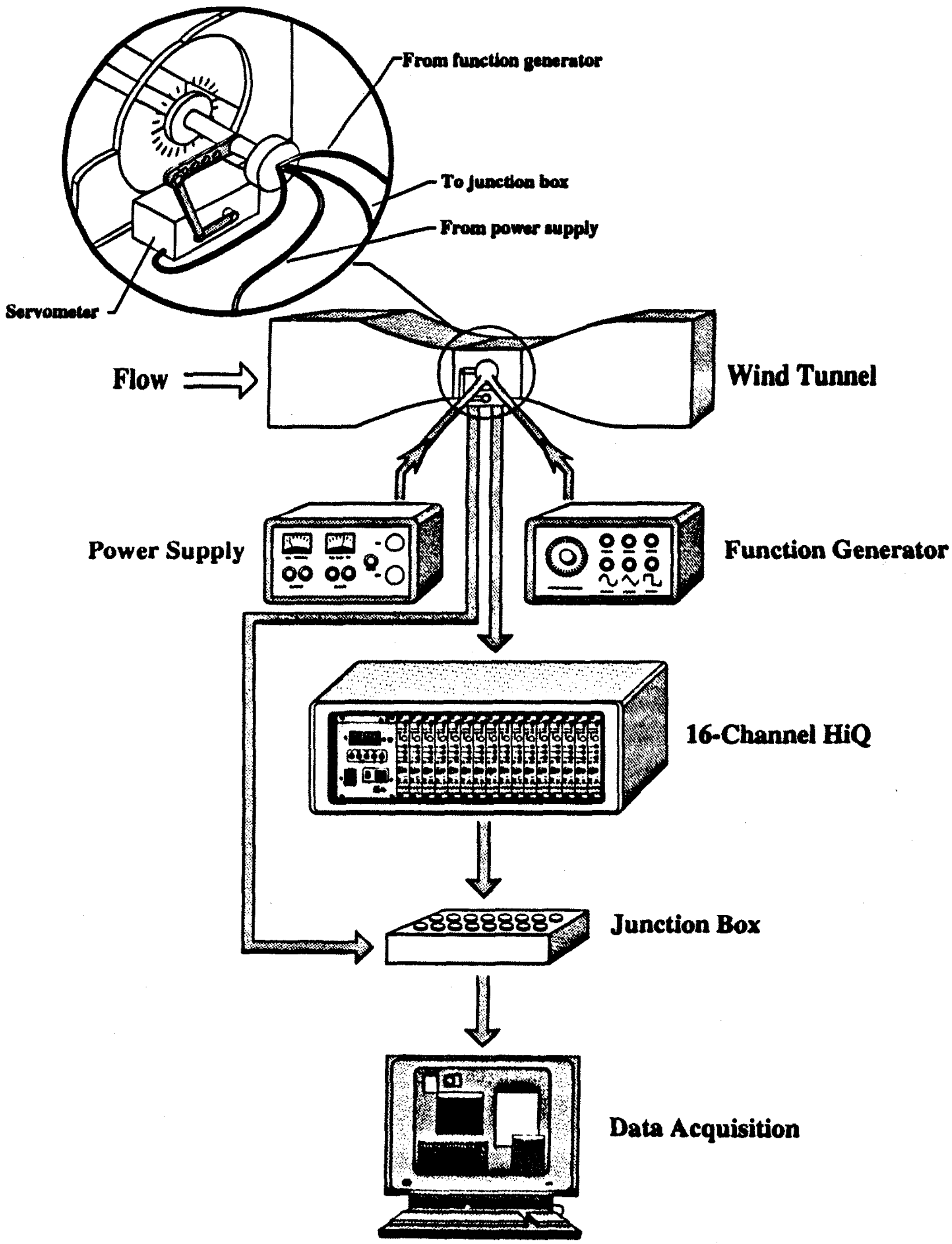


Figure 1. The experimental arrangement.

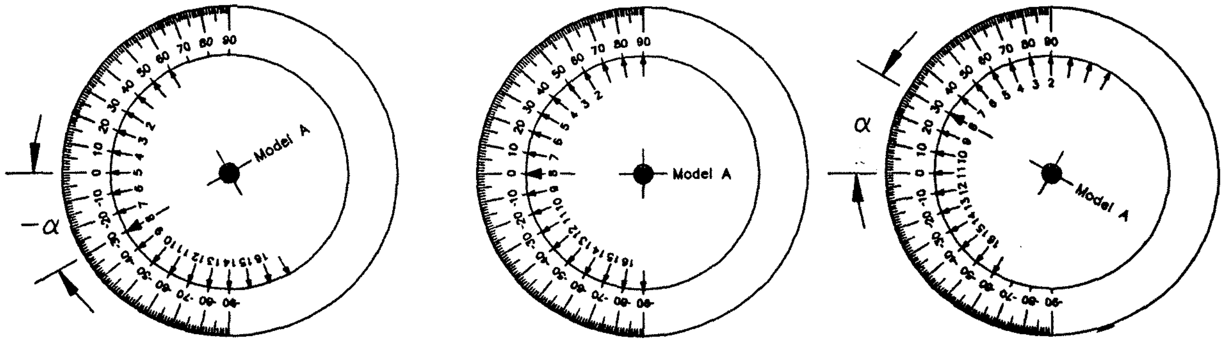


Figure 2. A few instantaneous positions of model A during its oscillation.

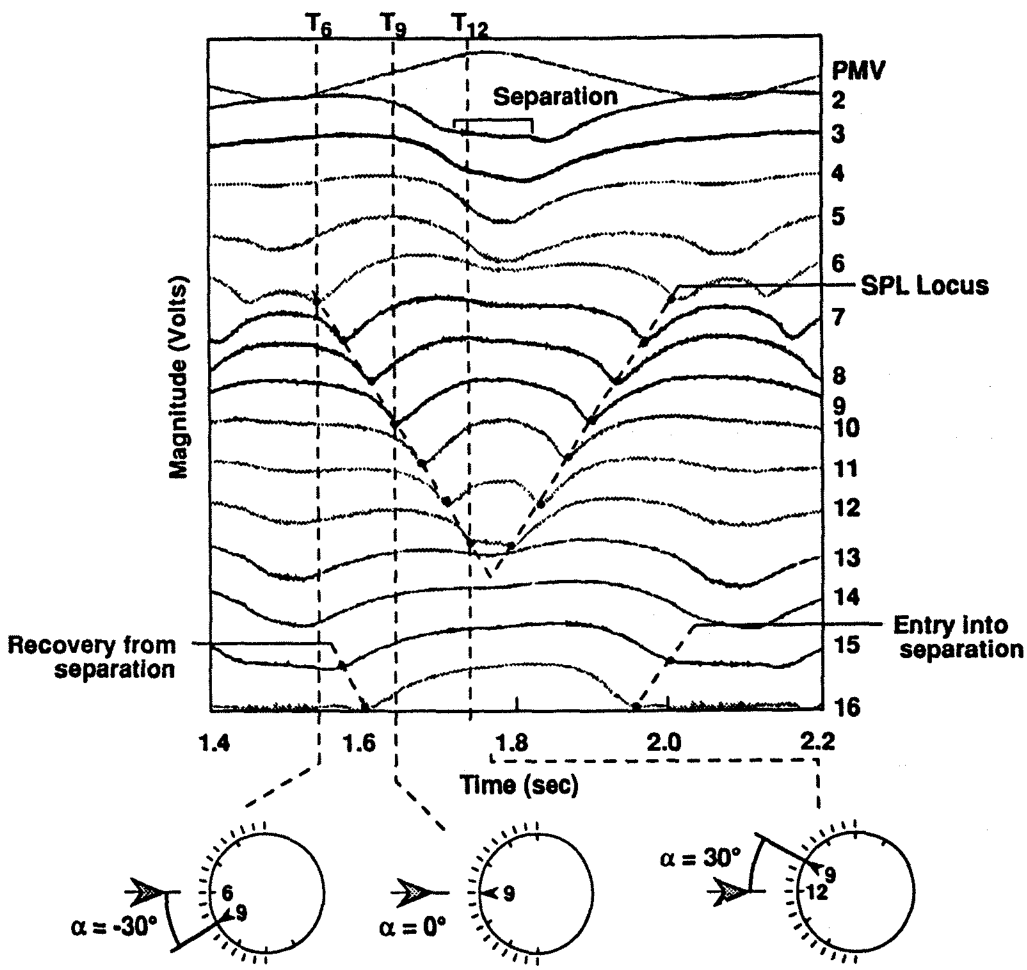


Figure 3. Spatial movement of the stagnation and separation points during a cycle of oscillation for model A.

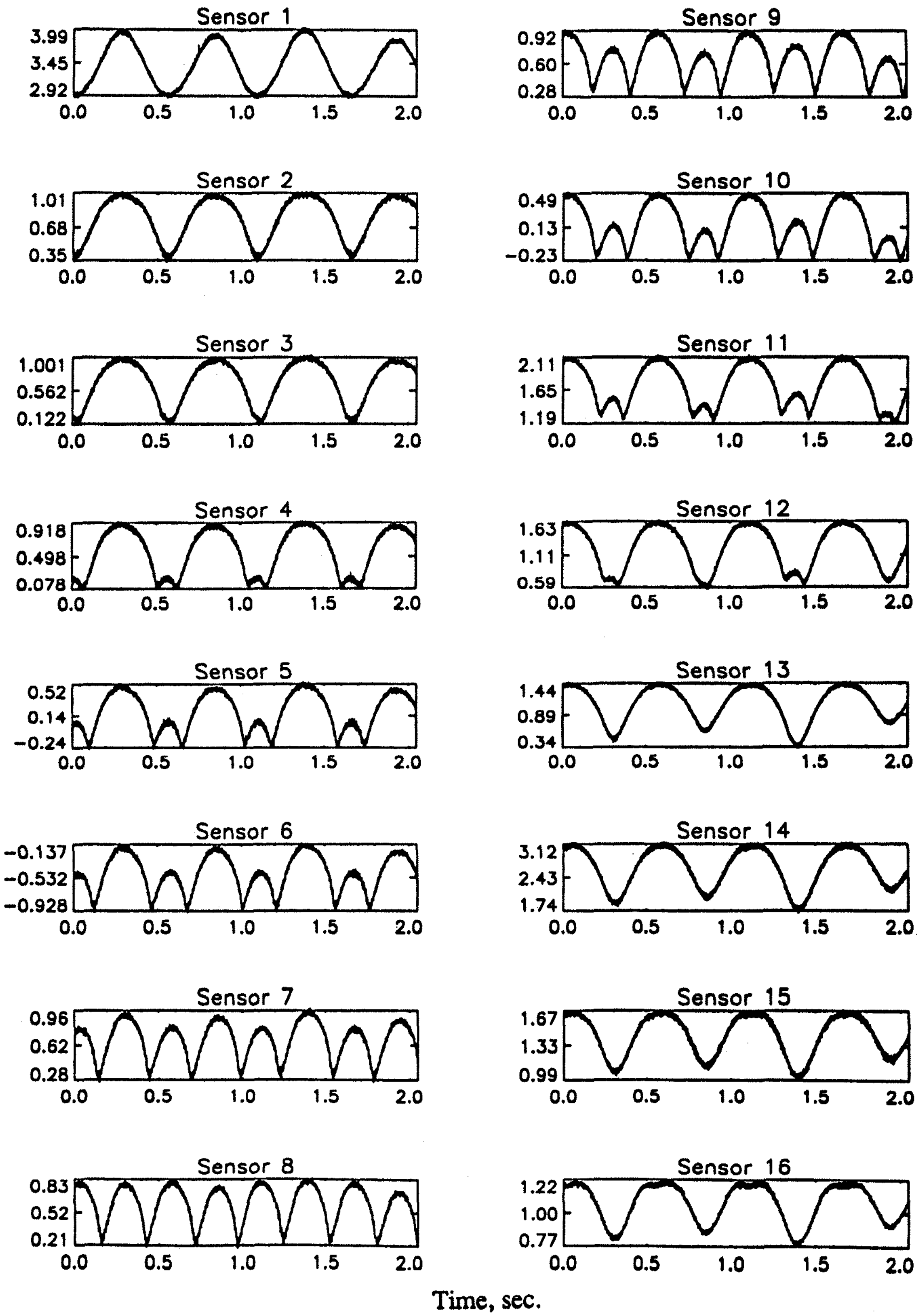
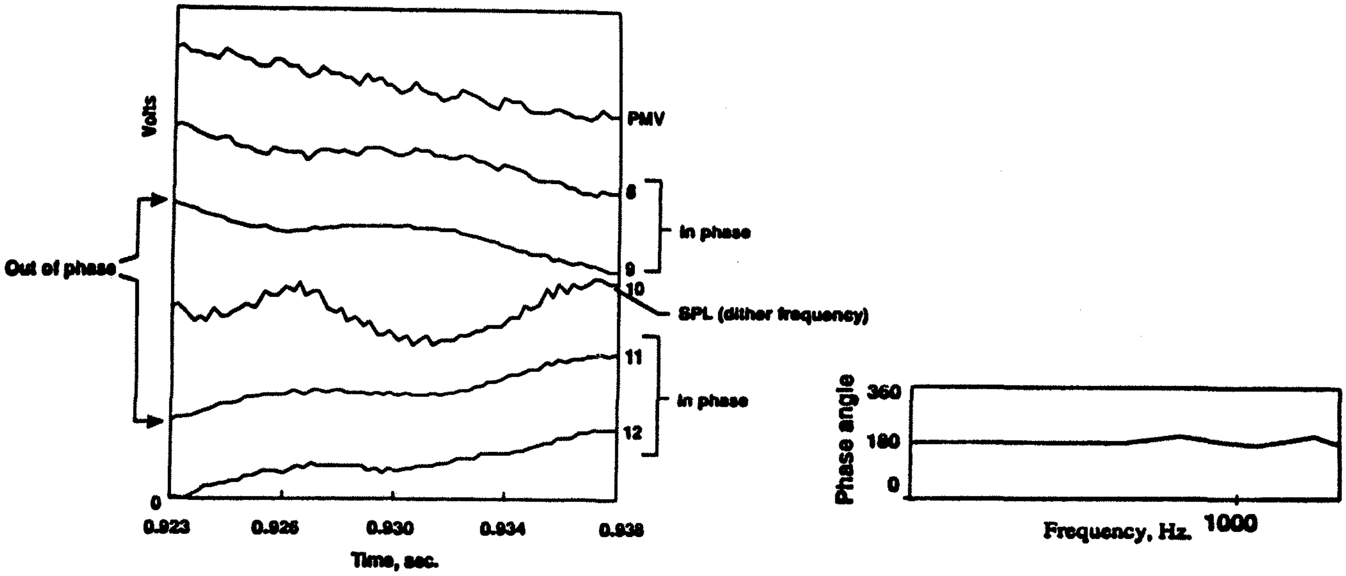


Figure 4. Time series for model B (Amplitude of Oscillation = ±15°; Frequency = 1.95 Hz).



(a) Time series showing PRS at sensor 10.

(b) Phase correlation for sensors 9 and 11.

Figure 5. Signals corresponding to the instant when sensor 10 is at stagnation.

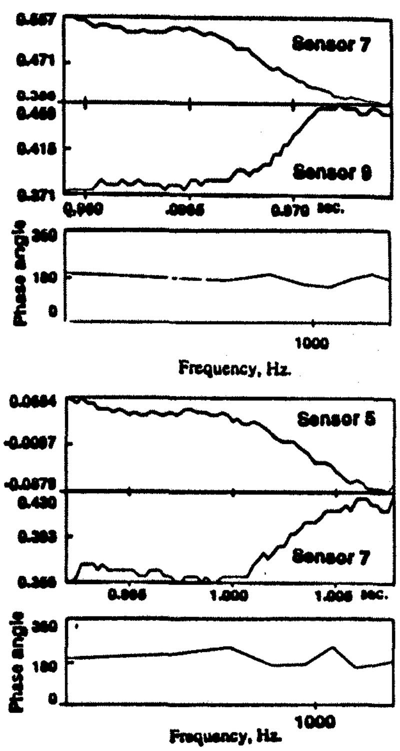


Figure 6. Phase reversals in mean signal voltage across the SPL at different instants of model motion.

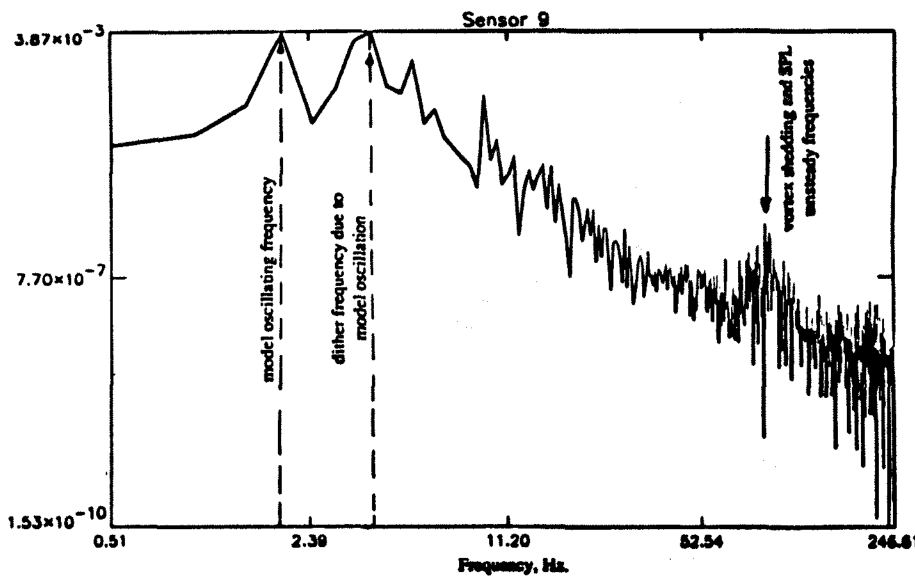


Figure 7. Autospectra for sensor 9 showing model and flow related frequencies.

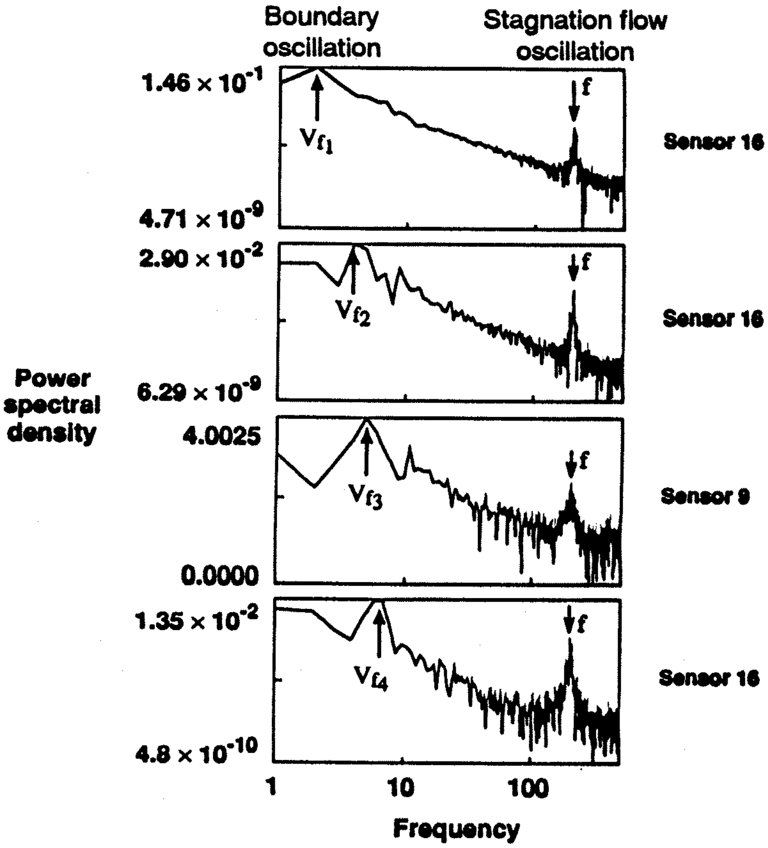


Figure 8. Invariance of flow oscillation frequency (f) with probe vibration frequency (V_f).

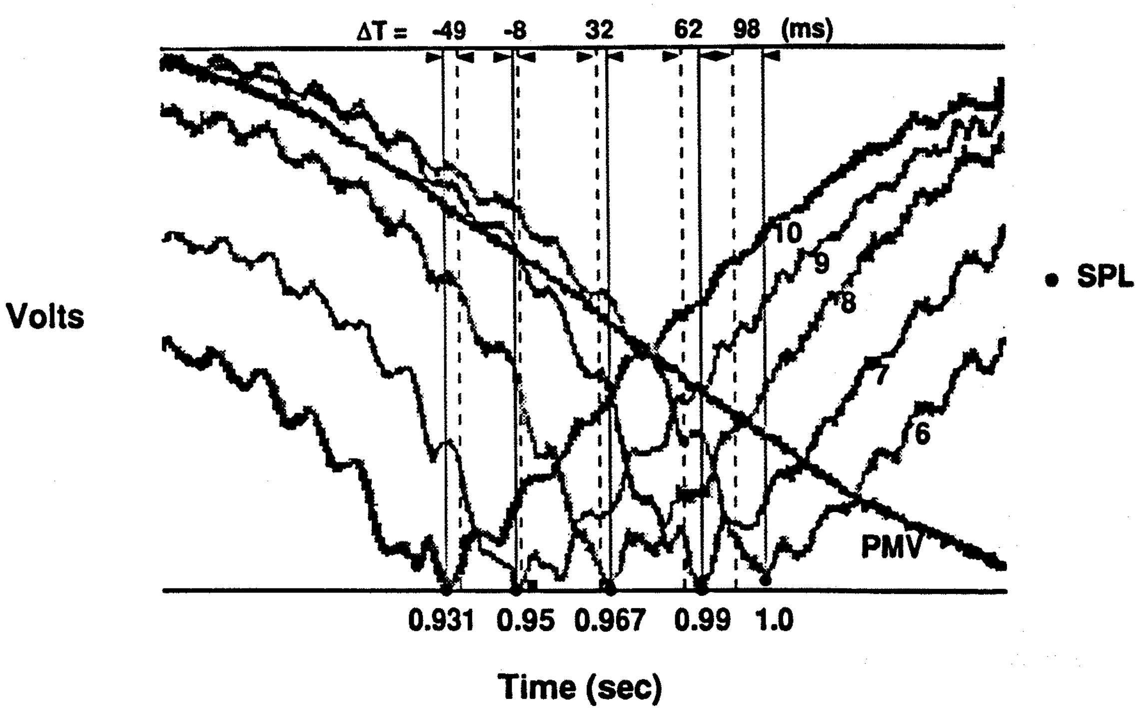


Figure 9. Exploded view of the stagnation point flow features for model B.