Concept and Technique for Probing Channel Flows with Abrupt Perturbations

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A widely used research technique for gaining information about the dynamic characteristics of flow systems is to introduce controlled, periodic perturbations to the flow and analyze the system's response. In some situations, use of single-pulse perturbations offers significant advantages over sinusoidal excitation. A technique has been developed for the repetitive imposition of large-amplitude (10–20%), rapid rise time (~75 μs), long-duration (~15 ms), ramp-shaped compressive disturbances (essentially weak shocks) on channel flows. The disturbance is created by the abruptly initiated and subsequently sustained injection of a secondary stream whose mass-flow rate is a significant fraction of the channel flow (10–20%). The amplitude of the pressure pulse depends on the injected mass-flow fraction and the channel-flow dynamic pressure at the place of injection. Details of implementation, measured performance, and initial operating experience are discussed.

Introduction

THE response of flows to controlled disturbances is a powerful diagnostic technique that has proved especially useful for the study of coherent structures in free shear layers and jets.[1-3] Repetitive introduction of suitable disturbances can regularize random processes, thereby greatly improving the conditions for their observation and study.

Most recent applications of these techniques involve low-speed flows and low-level, periodic, single-frequency perturbations, which are usually generated by loudspeakers. The technique allows the independent and precise control of both frequency and amplitude at a low cost.

Similar techniques are also used in the study of air-breathing propulsion systems, especially in connection with undesirable, system-scale oscillations.[4] The usual intent is to simulate a source of excitation (which is often a combustor), but the excitation may also serve the purpose of exploring the physics of the flow in much the same way as in fundamental studies of shear flows.

The amplitude of propulsion system fluctuations may be far greater (± 10% of mean pressure)[5,6] than that obtainable from loudspeakers; thus, the generation of realistic perturbations requires the use of mechanical devices.[7-9] These drivers are generally limited to low frequencies (< 400 Hz), and usually produce perturbations that contain significant contributions from higher harmonics. They rarely offer independent control of amplitude and frequency, leaving unresolved questions about the relative importance of frequency and amplitude effects.[9] Despite their shortcomings, such devices have been useful in exploring various flows and undoubtedly will remain standard tools of the propulsion trade.

The diagnostic potential of periodic excitation has some limitations, regardless of the amplitude of the excitation and the method used to create a disturbance. These limitations exist in systems displaying oscillations that contain more than one family of moving disturbances; e.g., upstream- and downstream-running longitudinal acoustic waves in slender channels. In such cases, measurements of fluctuating properties represent the summed contributions from all families of waves; therefore, the identification of individual contributions may not be possible. For instance, fluctuating channel flows with thick boundary layers may contain complex convective disturbances in addition to the two acoustic waves, and individual characterization of the three mechanisms is not possible on the basis of periodic data.[10]

Perturbing the flow with solitary pulses can accomplish the desired isolation. Figure 1 illustrates the example that motivated the present effort. The flow in a transonic diffuser is known to display self-excited fluctuations in which closely coupled acoustic and convective disturbances play significant roles.[11] Periodic excitation imposed at the downstream end provided much useful information about the flow,[8] but a separate assessment of each contributing mechanism was not possible in this approach. The *x-t* diagram included in Fig. 1 shows how isolation can be accomplished in the time domain if pulse perturbation is used. When introduced at the downstream end, the perturbation creates an upstream-moving weak shock or acoustic wave. When the wave reaches the shock, it creates downstream-moving disturbances whose speed, amplitude, and other properties may be studied.

Abrupt perturbations, apart from complementing periodic excitations as research tools, have advantages in the validation of unsteady numerical codes. Computations of forced periodic motions usually must deal with initial transients introduced by the arbitrariness of the initial conditions. Truly periodic solutions are obtained only after the decay of these transients. The use of periodic data for code validation therefore entails the inefficiency of having to discard the initial, nonperiodic portion of the results.[12] In contrast, a pulsed experiment is of short duration and all useful information is contained in the initial transients. The computational times are correspondingly short, making pulsed experiments attractive candidates for the validation of numerical codes.[13]

The present work was motivated by applications to propulsive flows experiencing large-amplitude perturbations. To explore such processes in the laboratory, we developed a device for the repetitive generation of large (up to 20%), abrupt changes of back pressure into a channel flow. Each pulse has a short rise time (~75 μs), and the elevated level can be sustained for relatively long times (~15 ms). This paper describes the design and construction of the device.

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Definition of Design Parameters

The application in question is a transonic diffuser flow with a rectangular exit cross section (16.5×6.7 cm) with typical flow rates of 2–3 kg/s, at atmospheric exhaust pressure and mass-flow-averaged exit Mach numbers of 0.4–0.5. The channel displays several modes of natural oscillations, with periods ranging from 3 to 10 ms (100–300 Hz), depending on the pressure ratio.[14]

The pressure rise imposed at the channel exit has to be short compared to the period of the oscillations, suggesting a ramp rise time of 30–100 μs. This requirement is extreme and well beyond the capabilities of commercially available devices: The fastest special-purpose valves whose descriptions we could locate in the literature featured opening times of approximately 1 ms.[15,16]

The severe rise-time requirement is aggravated by a conflicting need to sustain the high ramp level for a long time to avoid interpretation problems that would be associated with a variable exit pressure. This requirement in the current application implies a ramp level duration of at least one period of oscillation at the lowest natural frequency, i.e., approximately 10 ms. The largest disparity between these two time scales (300:1) is beyond the dynamic range of most mechanical devices.

The diffuser flow displays random fluctuations at low frequencies, and the response must be expected to vary, even if the exciter pulses are identical. Therefore, ensemble-averaging techniques should be used that require repetitive signals at a reasonably fast rate. Repetition at intervals of several seconds was considered acceptable.

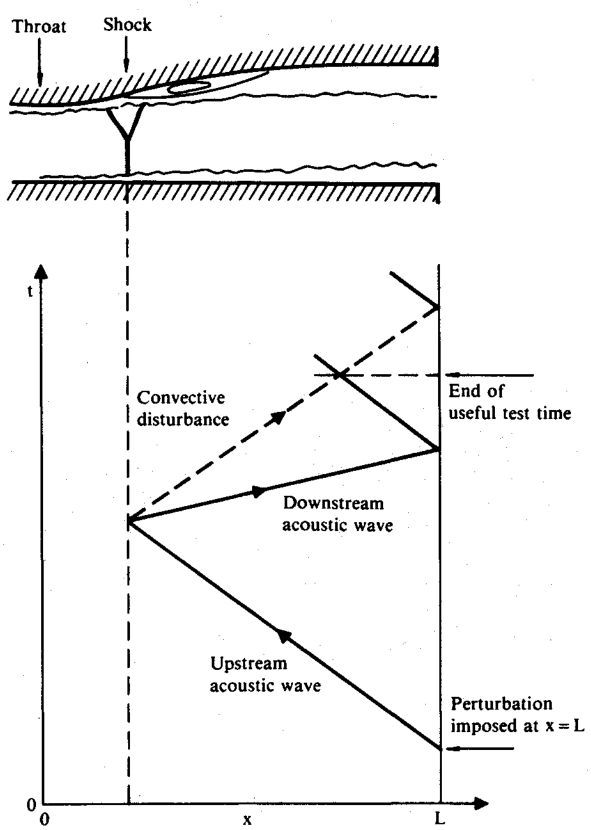

Fig. 1 Response of a transonic diffuser flow to an abrupt perturbation introduced at the downstream end.

Apparatus

Concept

The concept adopted to meet the stated requirements involves the abrupt injection of a mass flow into the main flow path. Estimates based on momentum integal considerations indicate that the pressure pulse height depends mostly on the injected mass-flow fraction and on the local dynamic pressure of the channel flow. Higher channel Mach numbers with the same injection rate and static pressure result in stronger pulses.

Figure 2 illustrates the concept of the pulse-generating system, shown assembled with a diffuser. Figure 3 presents details of the injection.

The perturbation is accomplished by the sudden injection of airflow through spanwise rows of small supersonic nozzles oriented nearly normal to the main flow direction. The source of air for the jets is a shock tube operated as a small shock tunnel. The shock created by the burst of the diaphragm travels toward the diffuser, reflects from the end of the tube, and creates a stagnant region of gas.[17] This gas has been compressed once by the orginal shock and once by its reflection. This double-shocked region (referred to as the primary plenum chamber) is used as a reservoir for supplying air to the nozzles, as indicated in Fig. 3.

The outside contour of the end of the shock tube is a streamlined centerbody that splits the diffuser stream into two branches (this portion of the sytem is referred to as the injector head). Rows of jets issue into each branch of the flow to

Table 1 Typical shock-tube conditions, based on gasdynamic calculations

Pressure in driver before firing	375 kPa
Pressure in tube before firing	100 kPa
Temperatures in tube and driver	300 K
Shock speed	460 m/s
Pressure of double-shocked gas	333 kPa
Temperature of double-shocked gas	428 K
Jet Mach number	1.43
Jet speed	500 m/s
Duration of steady jet flow	5.2 ms
Time for jets to traverse a channel branch (set to 2.0-cm height)	40 μs

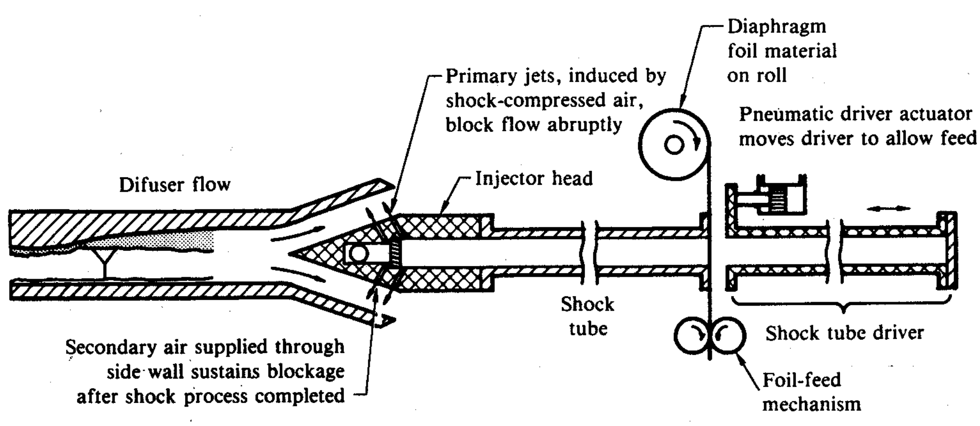

Fig. 2 Pulse-generating system. Solid rectangles marked PT are pressure transducers; PT1 indicates reference transducers.

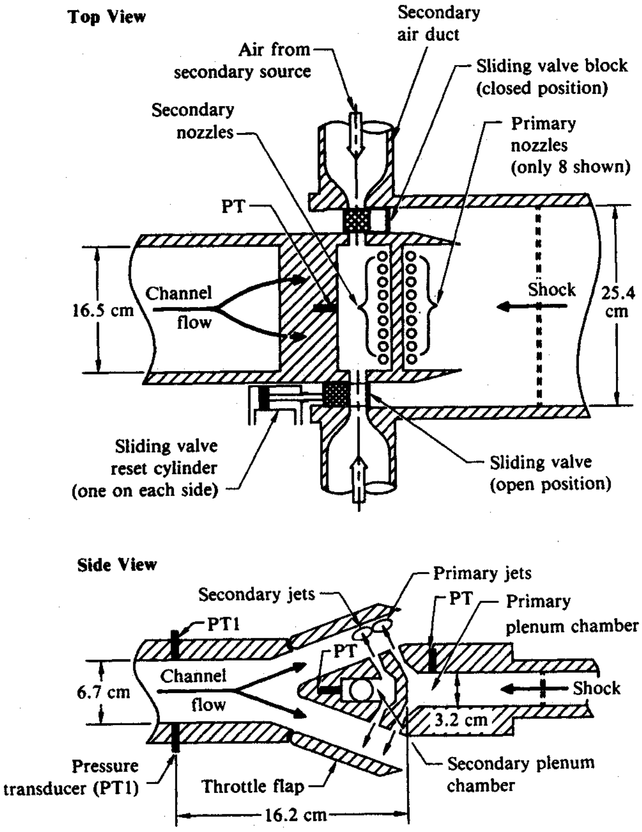

Fig. 3 Details of injector head.

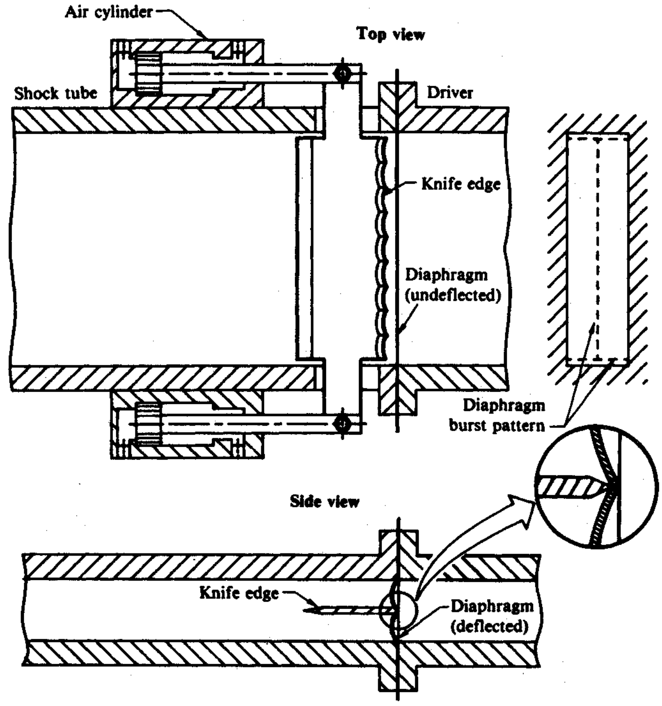

Fig. 4 Pneumatically activated knife edge used to puncture shock-tube diaphragm.

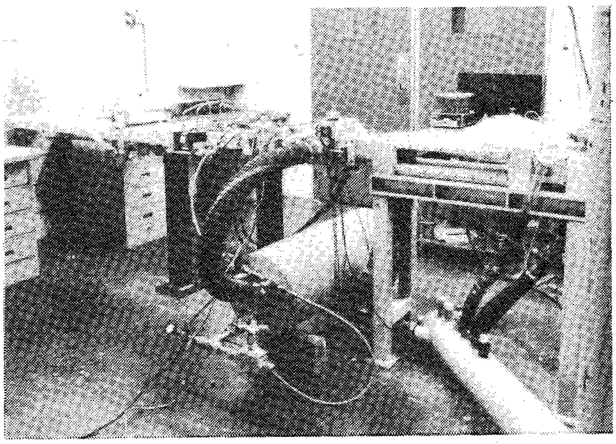

Fig. 5 Photograph of pulse generator attached to diffuser model. Tank on floor is secondary air source, located under injector head.

produce a symmetric perturbation. The split arrangement halves channel height, the time needed for the jet fluid to traverse the flow, and thereby the rise time of the pulse.

A typical condition for the shock tube, on the basis of gasdynamic calculations, is shown in Table 1.

Sixteen identical nozzles are arranged in a single row, one row on each side of the centerbody. The amplitude of the pulse varies in proportion to the total throat area, such that changing the nozzles is the most direct way of controlling pulse height. For this reason, the nozzles are machined into common, removable nozzle blocks (one for each side), which can be changed with relative ease. For a throat diameter of 4.2 mm, the total injected mass flow under the above conditions is approximately 0.29 kg/s (10–15% of the channel flow), producing pulse heights of approximately 15% of the mean static pressure just upstream of the injection station. An alternative method of controlling pulse height is to vary the shock-tube driver pressure: Increasing driver pressure increases pulse height and decreases pulse duration.

The pressure ratio of the diffuser flow is controlled by the two hinged throttle flaps shown in Fig. 3, one for each branch. The flaps can also be used to compensate for minor asymmetries in the diffuser flow. If the mass flows in the two branches are not equal, the pulses will not arrive at the main channel at the same time. Trimming is accomplished by adjusting the flaps until the pulses, as shown by the top and bottom wall pressure transducers (marked PT1 in Fig. 3, side view), coincide in time.

The shock-fed injection system is capable of the desired short rise time but is not suitable for sustaining the induced pressure rise long enough. The primary plenum pressure is constant only until the arrival of the driver gas (contact discontinuity, and after approximately 5 ms, the pressure in the primary plenum chamber drops rapidly.

Secondary Injection System

An opportunity to solve the sustainment problem is offered by the fact that the 5-ms operation of the shock tunnel (hereafter referred to as the primary injection system) is sufficiently long to allow the opening of a mechanical valve. The valve can be used to admit pressurized air from a separate source to continue feeding the injector jets. The duration of such a secondary injection is limited only by the size of the secondary air source, which can easily be made large enough to provide air for several tens of milliseconds.

It was convenient to design the secondary injection as a completely independent, parallel system with its own pressurized-tank air source, valve, a dedicated secondary plenum chamber inside the injector head, and separate rows of nozzles (Fig. 3). The secondary nozzle rows are parallel and close to the primary nozzle rows so that the shift from one system to the other has little effect on the diffuser flow several duct heights upstream.

The secondary plenum of the injector head is supplied with air across the sidewalls of the shock tube, as illustrated in the top view of Fig. 3. The shock tube is wider than the diffuser, to allow room for a valve on each side. Each valve consists of a single Teflon block, which slides in a passage of rectangular cross section. In the initial position, the block is at the downstream end of its travel, keeping the secondary air duct

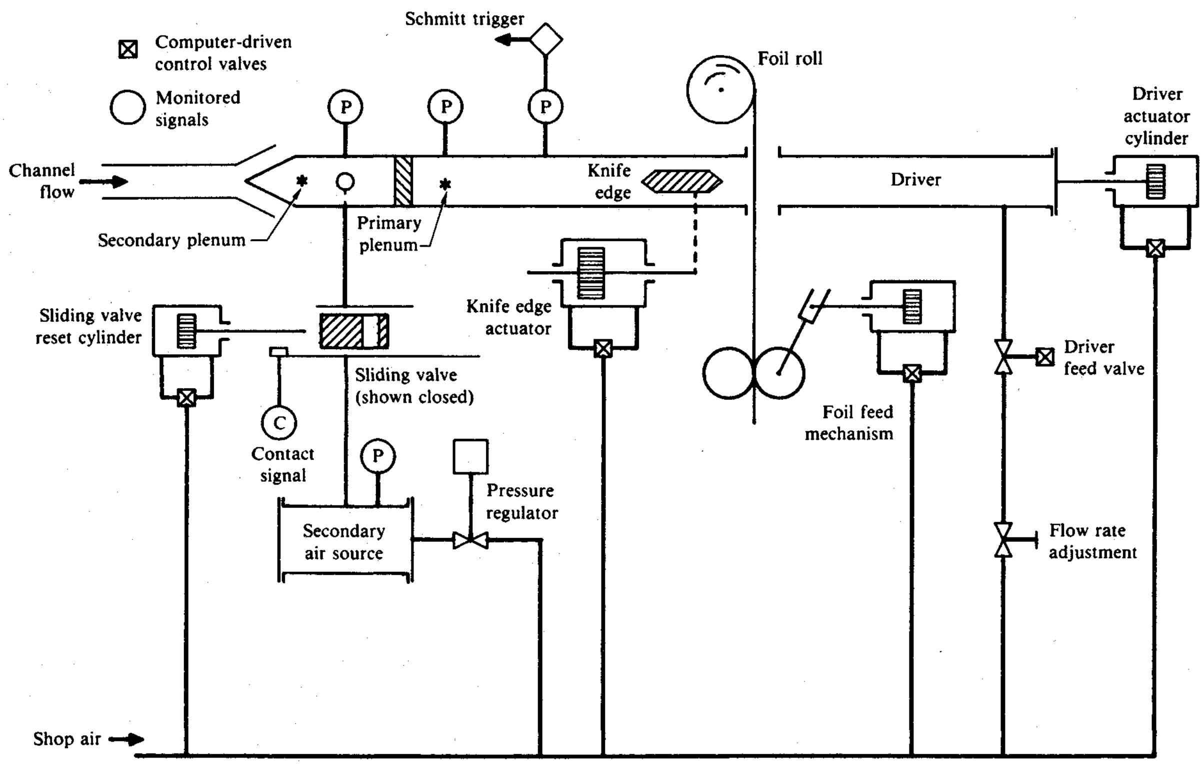

Fig. 6 Air supply and control system for injected flows.

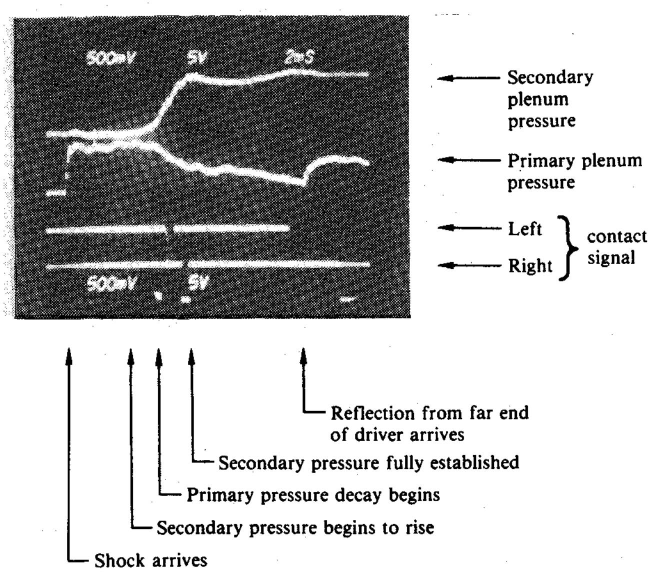

Fig. 7 Histories of primary and secondary plenum-chamber pressures during a perturbation event.

shut. When the shock arrives, most of it enters the primary plenum and initiates the primary jets, while the remainder continues in the two side passages until it reaches the sliding valves and sets them into motion. After several milliseconds, the holes bored into the Teflon valve blocks move into alignment with the secondary air-supply ducts and initiate the secondary airflow.

The secondary air source is a blowdown tank with a volume of 0.075 m^3, sufficient to maintain the required airflow for 15 ms with only a 10% drop in pressure. The tank is connected to a compressed-air supply through a pressure regulator and is automatically recharged after each use.

A pair of small pneumatic cylinders resets the sliding valves to their starting position after each shot.

A smooth switchover from the primary to the secondary air system requires that the sum of the pressures in the two plenum chambers be nearly constant during the switch. The shock-tube driver pressure, the mass of the sliding valve, the location of stops for the valve, the size of the hole in the blocks, the dimensions of the secondary air pipeline, and the secondary source pressure all affect the time history and can therefore be adjusted semi-empirically until the elevated level of the channel-pressure perturbation remains acceptably constant.

Diaphragm Design

The classical burst-diaphragm technique is used to begin the shock-tube cycle. Diaphragms made of 0.127-mm (0.005-in.)-thick, commercial, "dead-soft" aluminum foil produced bursts of nearly 390 kPa, a convenient operational level.

The shock tube has an unconventional, high-aspect-ratio, rectangular cross section, whose height and width were fixed by design constraints at 31.8 and 354 mm, respectively. Initial trials showed that foils clamped between flanges tend to display random burst patterns, usually limiting the flow to less than half the cross section. This problem was solved by installing a horizontal, full-span knife edge on the low-pressure side of the diaphragm, at half-height (Fig. 4). The pressure differential causes the foil to bulge, creating stress concentrations along the knife edge, which define the line of split. The knife edge was empirically contoured to produce a full-width, double-door-like split (the long sides of the cross section being the hinges). Initially, the pressure differential across the diaphragm was relied on to produce the burst, but this procedure led to a wide scatter of burst pressures (a Gaussian distribution with 5% rms). The operation was much improved by mounting the knife edge on a pair of hydraulic actuators, which pushed the knife toward the diaphragm at a computer-commanded instant whenever the driver pressure was at the desired level. This arrangement not only reduced the scatter by a factor of seven but also allowed considerable control over the burst pressure while still allowing use of the commercial, low-cost foil material.

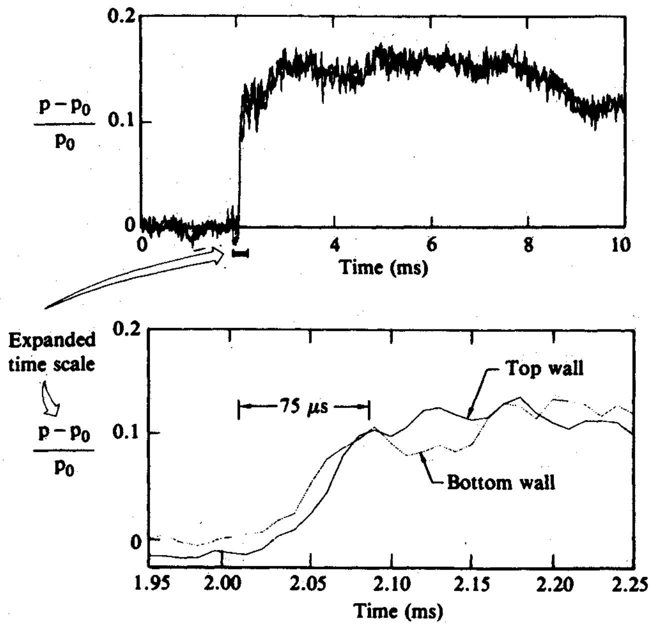

Fig. 8 Pressure histories (pulse shapes) generated in a diffuser flow at transducers PT1 (shown in Fig. 3).

Automation of Diaphragm Replacement

The required high repetition rates necessitated automation of diaphragm replacement; this operation was accomplished by the use of a pneumatically driven mechanical system. The driver is mounted on rollers that allow a horizontal movement of 2.54 cm. A pair of pneumatic cylinders retract the driver from the shock tube, thereby freeing the clamped diaphragm. The diaphragm material is used in the shape of a 30.5-cm (12-in.)-wide roll, mounted on a spool on the top of the stationary shock tube. After the driver is retracted, suitably located knurled feed rollers pull the foil downward, placing fresh foil between the flanges of the driver and the shock tube. The replacement cycle is then completed by a reverse stroke of the cylinders, which closes the driver and clamps in the new diaphragm. The cylinders are sized to keep the driver firmly closed in the pressurized state. A photograph of the pulse generator system is shown in Fig. 5.

Control and Data Acquisition

The air supply and control air lines are shown in Fig. 6. The perturbation cycle starts by loading in a new diaphragm and closing the driver. Next, the driver is pressurized, and the diaphragm burst is commanded when the desired pressure level is reached. The output of the driver pressure transducer is measured by a commercial voltmeter capable of detecting and storing the maximum attained value; this value is then recorded as a data element. The signal from a high-response pressure transducer located 55 cm from the end of the shock tube is fed to an analog Schmitt trigger. The trigger initiates high-speed digitization of the injector-head plenum chamber pressures and all other data to be acquired from the diffuser. The cycle time is approximately 4 s.

All the required control and data-acquisition functions are performed by a computer, which also checks the acquired data. If any test parameter is not within a specifiable tolerance, then the data for the particular shot are rejected. Individual and ensemble-averaged signal histories from any selected sensor can be displayed immediately: The sequence of shots is complete if the averaged signal no longer changes significantly.

Performance

Figure 7 is an oscilloscope trace taken in a run using both systems. The data record contains the two injector-head plenum pressures and two contact signals that indicate the arrival of the valve blocks at the limit of their travel.

The oscillogram shows that the device performs as expected. The primary plenum pressure rises extremely rapidly, stays nearly constant for approximately 6 ms, and then decays. The secondary pressure begins to rise before the primary pressure decay, reaches the ramp level within 3 ms, and stays at the high level for the rest of the time shown. Approximately 15 ms after the initial pulse, the primary plenum pressure shows another abrupt rise, which is atributed to the return of a reflection from the far end of the driver, ending the useful portion of the cycle. The traces are highly reproducible.

The primary pressure rise contains a short, horizontal plateau midway in the rise. This interruption is related to the location of the transducer, 28 mm away from the end wall; the duration of the plateau signifies the time elapsed between the passage of the original shock and its reflection over the transducer. The nozzles, being located at the end wall, experience a single, uninterrupted pressure rise. The initial rise to the plateau lasts $\sim 30\ \mu s$.

The high pressure level shows an 800-Hz frequency jitter, which was traced to longitudinal acoustic oscillation in the valve-block passages, excited by the arrival of the shock. If necessary, these oscillations might be damped by the use of sound-absorbent wall materials.

The bottom two traces (from the contact detectors) indicate nearly equal travel times for the two valve blocks; differences in friction and/or tightness of fit probably account for the deviation. The signals also show an immediate loss of contact; the blocks elastically rebound from their stops, partially reclosing the openings. This bounce causes a temporary reduction of the secondary plenum pressure (lasting ~ 6 ms), which is clearly visible in the second trace. A spring-loaded arrester was later installed to keep the blocks in the fully open position after arrival.

Figure 8 illustrates the pulse shape detected by pressure transducers located just upstream of the pulse generator (Fig. 3). The rise time is $\sim 75\ \mu s$, which is quite satisfactory for the experiment in question. The signal contains higher frequencies that may be related to transverse oscillations or to longitudinal oscillations within the two branches of the generator. These frequencies were much higher than those characterizing the events of primary interest and did not interfere with the formulation of definite conclusions.

Other Potential Applications

In this section, some comments are offered concerning the suitability and limitations of single-pulse diagnostics to other flows.

The technique is considered here in the context of subsonic and transonic channel flows, in which the undisturbed flow and the disturbance are both one-dimensional to a first approximation. Within this class, the concept has potential for application to many situations.

In general, single-pulse experiments are appropriate if they create some fluid dynamic process of interest in pure form during the subsequent transients. The location at which the disturbance is introduced must be chosen to suit this purpose.

The sudden introduction of a disturbance into a subsonic flow induces changes both upstream and downstream of the point of introduction. The upstream and downstream consequences are fundamentally different; the former effects are created solely by acoustic-wave propagation, whereas downstream effects include both convection and acoustic-wave propagation. It follows that the introduction of a disturbance at the downstream end of a channel segment initiates a process entirely different from that which the same disturbance would cause if introduced at the upstream end.

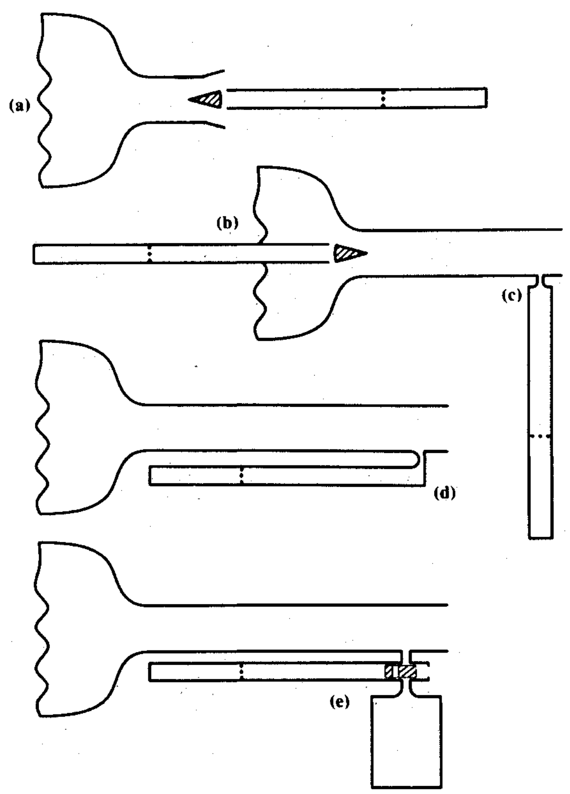

Fig. 9 Possible shock-tunnel arrangements for the generation of abrupt perturbations: a) injection downstream, shock-tube colinear; b) injection upstream, shock-tube colinear; c) injection downstream, shock tube normal to flow; d) injection downstream, shock tube parallel; e) shock tube actuating blowdown tank valve located downstream.

The methods needed to generate appropriate pulses are strongly dependent on the configuration in question, on the pulse shape desired (which includes such parameters as rise time, amplitude and sign of pressure change, and duration), and not very much can be said about the possible solutions in general. They may, in principle, be generated either by abrupt changes in the solid boundary of the flow or by a suitably arranged injection of secondary fluid (or removal by suction if an expansion pulse is desired). Compressive disturbances are simpler to create than expansion waves; the latter are expected to broaden, and their rise times might not be made sufficiently short to serve the intended purpose.

The present application is difficult, demanding large amplitudes, short rise time, long pulse duration, and repetitive operation. These difficulties forced the combination of several techniques to implement the conceptually simple central idea. These techniques are 1) a shock tunnel to generate the disturbance abruptly, 2) a secondary injection system to increase the pulse duration, 3) the use of the shock tunnel to actuate the secondary injection system valves, and 4) repetitive operation and ensemble averaging.

Other applications may be more forgiving and permit implementation by simpler means, requiring only some or even none of the techniques listed above. For instance, a simple blowdown tank with a solenoid valve could be used to generate pulses if the rise time and duration requirements are lenient enough. Another solution might be to move, in or out of the flow, a single, lightweight mechanical obstruction by means of springs. If a short rise time is desired, then a shock tunnel could be used to move this obstruction, in the same way the secondary valves are moved in the present apparatus. Since a mechanically moved component can be held in its new position indefinitely, the short duration of the shock-tunnel pulse would not limit the attainable pulse duration. The rise time could be made very short with the use of high driver pressures.

The layout of the shock tunnel is not limited to the colinear arrangement used in the present design; the shock tunnel may be located normal to the flow direction or parallel to the main flow, as indicated in Fig. 9. Rectangular or axisymmetric arrangements are both feasible.

Summary

A device was developed to introduce compressive disturbances into a channel flow system. The disturbances have large and adjustable amplitudes, extremely short rise times, and can be sustained for relatively long periods. The disturbances can be generated repetitively, in approximately 4-s intervals. These capabilities allow the determination of the ensemble-averaged response of various internal flows to large-amplitude pulses. From this response, the propagation and reflection characteristics of acoustic and convective disturbances can be determined. The technique is suitable for a variety of flows although the details of implementation depend on the specific application.

Acknowledgments

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