Supersonic Inlet-Torsional Cascade Flutter

Sanford Fleeter,* Robert B. McClure,† George T. Sinnet,‡ and Robert L. Holtman§
General Motors Corp., Indianapolis, Ind.

Currently there is a dearth of fundamental dynamic aeroelastic cascade data with which to validate and/or indicate necessary refinements in mathematical models of such phenomena. This paper describes a unique supersonic inlet with a subsonic axial component, torsional flutter cascade experiment, wherein a computer controlled electromagnetic airfoil excitation system is used to simulate the fundamental time-dependent airfoil interaction, assure physical periodicity, and control the interblade phasing angle. Experimental data are presented which indicate the variation and significance of the cascade inlet Mach number, the stagger angle, and, in particular, the interblade phasing angle on the cascade dynamic torsional aeroelastic characteristics.

I. Introduction

IN the development of compact, lightweight, compressor and fan components for advanced engine configurations, improvements in airfoil aerodynamics are limited by dynamic aeroelastic constraints. Current interest is directed towards determining and understanding the torsional aeroelastic characteristics of compressor and fan stages in a supersonic inlet flowfield with a subsonic axial component.

Analytical investigations of the fundamental unsteady, supersonic inlet cascade aerodynamic problem with both a subsonic[1-4] and a supersonic[5,6] axial component (see Fig. 1) are beginning to appear in the literature. However, at present, there is a dearth of fundamental supersonic inlet unsteady aerodynamic cascade data with which to validate and/or indicate necessary refinements to these mathematical models.[7]

For the case of a steady supersonic inlet cascade flow with a subsonic axial component, the inlet conditions to any airfoil passage are determined by the stationary position and geometry of the preceeding airfoils relative to the undisturbed flow ahead of the first airfoil in the cascade, as seen in Fig. 1. Under this condition, periodicity in the steady flowfield of succeeding airfoil passages is achieved with relatively few airfoils—on the order of 5.[8-10]

However, for time-dependent supersonic inlet cascade flow with a subsonic axial component, the inlet flow conditions to any airfoil passage are dependent not only on the geometry and the position of the preceeding airfoils in the cascade, but also on their relative motion, as indicated in Fig. 1. Hence, a supersonic inlet with a subsonic axial component free flutter test of a 5 airfoil cascade, such as that described in Ref. 11, does not appear to simulate this time-dependent airfoil interaction.

This paper describes a supersonic inlet with a subsonic axial component time-dependent cascade experiment wherein a unique airfoil excitation system is used to simulate the previously described unsteady airfoil interactions, to assure physical periodicity, and to control the interblade phase angle, thereby permitting meaningful supersonic inlet torsional flutter data to be obtained with a 5 airfoil cascade.

Presented as Paper 74-530 at the AIAA 7th Fluid and Plasma Dynamics Conference, Palo Alto, California, June 17-19, 1974; submitted October 2, 1974; revision received December 5, 1974. This research was supported in part by the Power Branch of the Office of Naval Research under Contract N00014-72-C-0351.

Index categories: Nonsteady Aerodynamics; Aeroelasticity and Hydroelasticity.

*Section Chief—Cascade and Flow Systems Research. Member AIAA.

†Section Chief—Measurement Systems Research. Member AIAA.

‡Principal Engineer—Data Acquisition Systems.

§Senior Research Engineer.

II. Airfoil Cascade and Schlieren System

To experimentally evaluate the assumptions required by the various mathematical models currently being developed to describe supersonic inlet unsteady aerodynamic cascade phenomena, a cascade of 5 flattened double-wedge shaped airfoils was designed and fabricated. The cascade parameters were chosen to be representative of advanced fan and compressor designs and are presented in Table 1.

Each airfoil is cantilevered from a trunnion which is attached to a torsion rod, as seen in Fig. 2. Strain gages are mounted on each torsion rod and each airfoil, with each of the airfoils having a gage for bending and one for torsion.

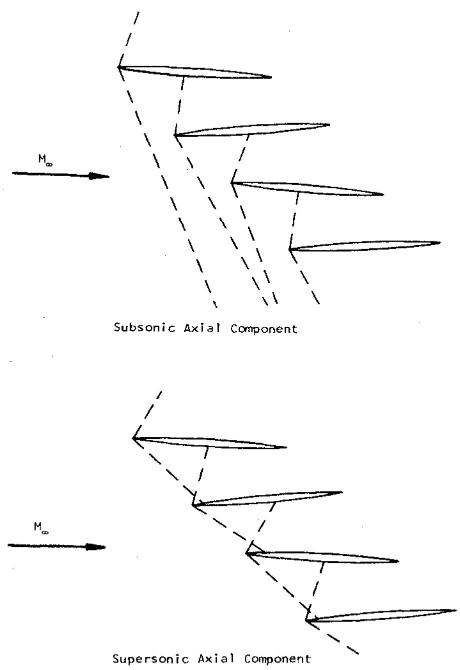

Fig. 1 Supersonic cascade inlet flowfields (180° interblade phase angle).

Table 1 Cascade physical design parameters

Airfoil chord (in.)	2.50
Cascade solidity	1.21
Airfoil span (in.)	3.02
Thickness/chord (max)	0.04
Stagger angle No. 1	61.09°
Stagger angle No. 2	66.09°

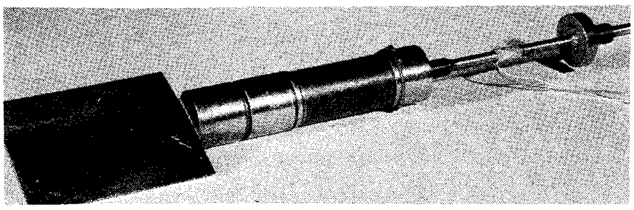

Fig. 2 Airfoil-trunnion-torsion rod assembly.

A steel sidewall with an inset back surface glass mirror was fabricated. This mirrored sidewall serves as a wind tunnel test section wall as well as a reflective surface in a double-pass schlieren system, thereby providing flow visualization. The double-pass schlieren system, shown schematically in Fig. 3, utilizes a mercury vapor light source. The plane mirrors *A* and *B* and the 16-in. parabolic mirror *C* are adjusted such that the light is collimated by *C*. This collimated beam passes through the wind tunnel test section to the mirrored tunnel sidewall and is then reflected back by the mirror system to the light source. The plane mirror *D* is then inserted into the system and the parabolic mirror *C* rotated slightly so that the reflected image strikes mirror *D*. The beam reflected from mirror *D* is then aligned with the knife edge and the lens of a high-speed 16 mm movie camera. The color schlieren, achieved by replacing the knife edge with a tri-color filter, results in improved visual flow analysis in that it greatly increases the ability to distinguish between the flowfield and the test model as well as different regions of the flow.

Each cantilevered airfoil-torsion rod assembly is then inserted through the mirrored sidewall (see Fig. 4) with the trunnion being mounted on ball bearings. On the back side of the mirrored sidewall, an airfoil driving arm is attached to each of the torsion rods. An electromagnet is provided for each of the driving arms to allow the on-line instrumentation system to drive the electromagnets at a prescribed frequency and interblade phasing angle and they, in turn, drive the airfoils in torsion at this prescribed frequency and phasing angle.

III. Facility and Instrumentation System

The supersonic cascade wind tunnel permits the testing of airfoil designs through a wide range of Mach numbers, setting angles, incidence angles, and pressure ratios. This tunnel uses 10 lb_m/sec. of filtered, dried, and temperature controlled air and is a continuous flow, nonreturn system. The exit of the test section is evacuated by steam ejectors which can maintain an exit pressure of 6 $lb_f/in.^2$ at the design flow rate.

The major features of the facility include the following: a) A mechanized test section which permits a cascade of airfoils to be rotated while the tunnel is in operation. b) A top and bottom bleed system which prevents the nozzle boundary layers from entering the cascade flowfield. They also provide paths for spillage so that the cascade inlet and exit operate independently. c) A sharp wedge which is independently mounted upstream of the cascade. The cascade inlet flow direction and Mach number are determined by the orientation of the wedge with respect to the airfoils and the nozzle flow, respectively. d) The schlieren optical system previously described. e) A sophisticated instrumentaion system which is centered around two digital computers. These computers provide rapid on-line control of cascade operation, data acquisition, data reduction, and calculate performance parameters.

The main experiment monitoring computer has a 16,000 word (16K) memory while the second computer has an 8,000 word (8K) memory. The computers and associated peripheral equipment are used to: a) Determine the cascade steady-state flow parameters including the inlet Mach number, inlet air density, cascade static pressure ratio, etc. b) Initiate and precisely control the time-dependent cascade operation including the interblade phasing angle. c) Digitize the time-dependent strain gage signals from each airfoil at rates to 100,000 points per sec. d) Permanently store the steady-state performance and time-variant data. e) Control a dual channel storage oscilloscope to provide an analog record of the time-variant strain gage output. f) Control a high-speed motion picture camera enabling high-speed color schlieren movies to be obtained of the time-dependent cascade phenomena. g) Analyze and plot the digitized cascade time-variant data online while the test is being conducted.

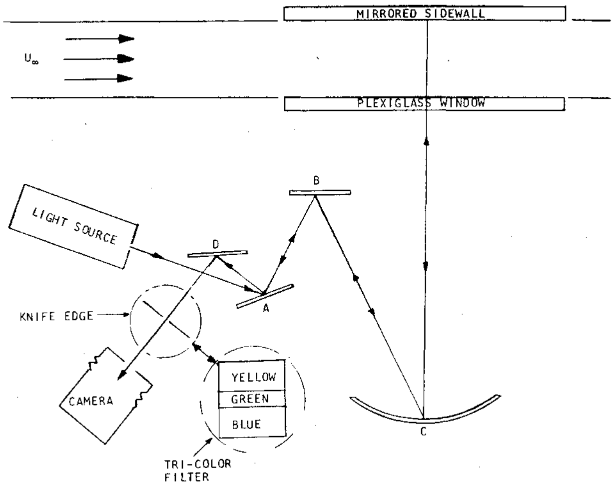

Fig. 3 Double-pass color schlieren system schematic.

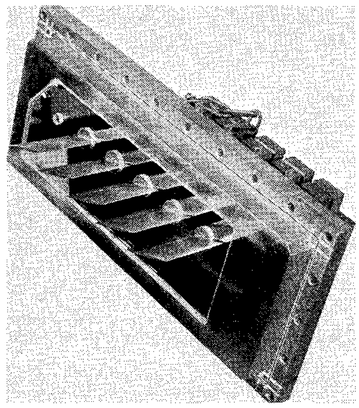

Fig. 4 Airfoil cascade cantilevered from the mirrored sidewall.

The 16K computer is utilized in part to determine the cascade steady-state flow parameters by controlling instrumentation, acquiring data from the cascade, and analyzing the data to provide the required performance parameters. In the control mode, the 16K computer operates a digital voltmeter, an electronic scanner, Scanivalve stepping motors, and the system peripheral equipment. During wind tunnel operation, the computer is capable of automatically acquiring any data required to establish the cascade operating characteristics. Pressure measurements are obtained by utilizing a system incorporating four 48-port rotary valves (Scanivalves) providing a total steady-state pressure measurement capacity of 192 pressures. In addition, up to 48 temperature measurements are possible. During data acquisition, the computer obtains 3 reference calibration pressures providing on-line calibration of the Scanivalve pressure transducers. Also, the computer monitors the cascade inlet total pressure and total temperature during this time period to ensure that cascade operating conditions do not vary outside a preset tolerance. The cascade data are analyzed on-line to establish the steady-state performance.

IV. Time-Dependent Cascade Operation

Dynamic testing to investigate and correctly simulate the cascade time-dependent characteristics in a supersonic inlet flowfield with a subsonic axial component requires the air-

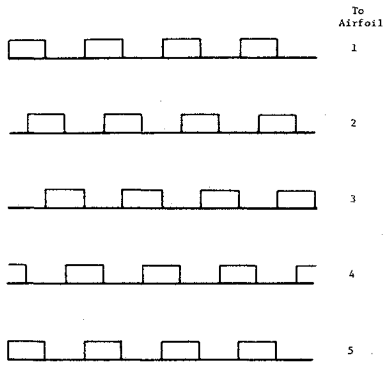

Fig. 5 90° interblade phase angle square wave driving signal output by 8K computer.

foils to be periodically excited at known frequencies with the interblade phase angle being precisely controlled. To accomplish this, the 8K computer generates a one-half square wave voltage signal for each airfoil at the specified excitation frequency with the required interblade phase angle imposed between the signals, as indicated in Fig. 5. The square wave signal for each airfoil corresponding to the cascade excitation frequency, and interblade phasing angle is repetitively generated and transmitted to the 16K computer.

As previously described, the cascade assembly was designed so that the time-dependent motion of each airfoil could be controlled by individual electromagnets which are interfaced with the 16K computer. Thus, the 16K computer can excite any or all of the airfoils in an harmonic torsional motion by transmitting to the electromagnets any or all of the half square wave signals being generated by the 8K computer. This provides the instrumentation system with the capability to initiate and precisely control the cascade excitation frequency and interblade phase angle. Additionally, the 16K computer can remove the driving power to any or all of the electromagnets precisely in the sequence of events necessary to acquire a complete set of parameters. A schematic of this computer controlled time-dependent instrumentation system is presented in Fig. 6.

V. Test Procedure

The testing program proceeds as follows. With the cascade assembly mounted in the test section, the cascade is tuned; i.e., adjustments are made so that all of the blades have the same fundamental torsional frequency. At this point, the tunnel is started and the cascade inlet Mach number, inlet air density, and back pressure are set. The specified oscillatory frequency and interblade phase angle are then input to the 8K computer which then calculates the corresponding half square wave generation sequence and outputs these signals to the 16K computer.

To begin the time-dependent experiment, the 16K computer transmits the half-square wave signals from the 8K computer to the corresponding electromagnets. This results in harmonic torsional oscillation of the airfoils at the specified oscillatory frequency and interblade phase angle.

Responses to the following items are input to the 16K computer and determine the exact experimental procedure. a) Should the high-speed movie camera be triggered? b) Should the storage oscilloscope be triggered? If yes, when? c) From which airfoils should the driving half-square wave be removed? When? For what time period? d) At what rate should the data be digitized? e) Should the digitized signals be plotted?

The process to control, acquire, and analyze the time-dependent experimental data is completely controlled by the 16K computer. The general sequence of events to determine cascade time-dependent performance is now presented.

With the tunnel in operation and the airfoils oscillating, the computer first applies power to the high speed movie camera.

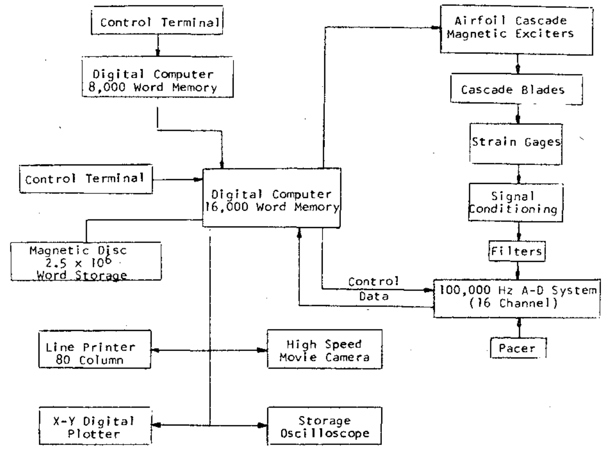

Fig. 6 On-line computer controlled time-dependent data acquisition schematic.

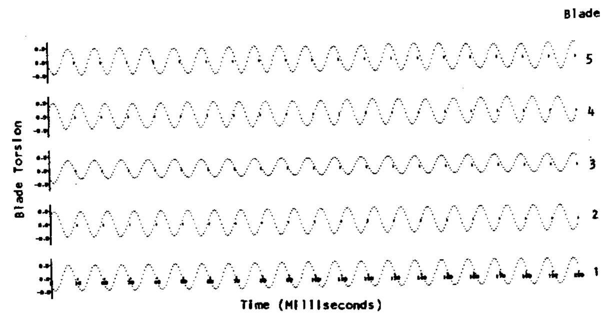

Fig. 7 Computer plot of digitized strain gage signals during 180° interblade phase angle flutter.

After a variable time delay to allow the camera to acquire full speed (approximately 750 msec at a rate of 5,000 frames per sec), the storage oscilloscope is triggered to record airfoil strain gage signals vs time. Fifty msec later, the computer stops transmitting the driving signals to the specified electromagnets. Immediately thereafter, the resulting time-dependent airfoil strain gage signals are digitized at rates to 100,000 points per sec employing the 16-channel analog-digital converter and multiplexer system. After 6000 data points have been acquired, the airfoil driving signals are restored along with the camera and oscilloscope triggers. These dynamic data and the corresponding cascade steady-state performance parameters are stored permanently on a removable magnetic disk (data storage capacity of over 1,000,000 individual data points per disk). The digitized time-dependent signals are then plotted and analyzed on-line with the time-dependent performance results presented on the line printer.

VI. Time-Dependent Data

The time-dependent data are analyzed on-line to determine: a) Aerodynamic damping, interblade phase angle, and oscillatory frequency at operating conditions where the cascade is stable; i.e., where the oscillations decay with time after the driving signals to the electromagnets are removed. b) Flutter frequency and interblade phase angle at operating conditions where the cascade is unstable; i.e., where the oscillations do not decay with time after the driving signals to the electromagnets are removed.

Aerodynamic damping values are determined from the logarithmic decrement of the decaying oscillations, and the interblade phase angle values are calculated between adjacent airfoils in the cascade. The aerodynamic damping, interblade phase angle, and frequency data are determined cycle-to-cycle and also averaged over the total number of cycles.

To check out this unique time-dependent experimental technique wherein 2 digital computers are used to control, acquire, and analyze data, a single airfoil was tested. The

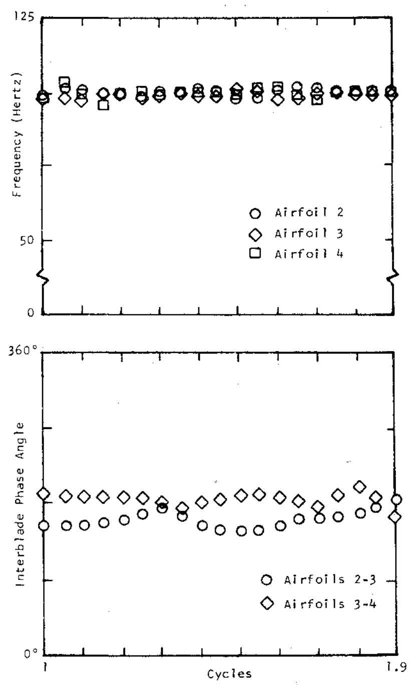

Fig. 8 Flutter frequency and interblade phase angle as a function of the number of cycles for a 1.60 inlet Mach number and a 61.09° stagger angle.

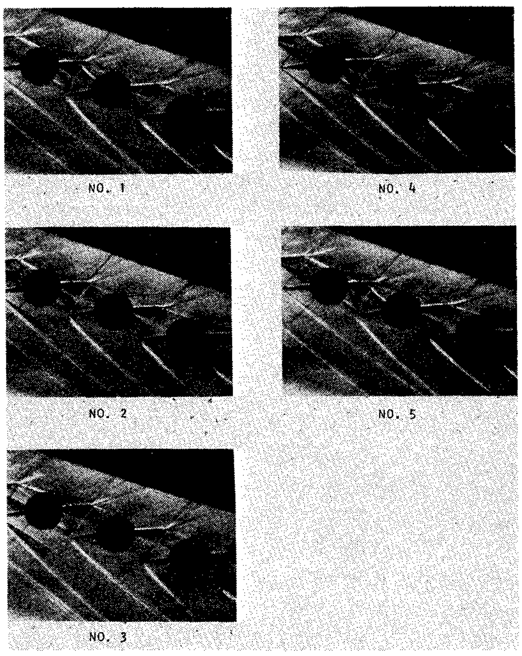

Fig. 9 Sequence from high-speed schlieren movie with 180° interblade phase angle.

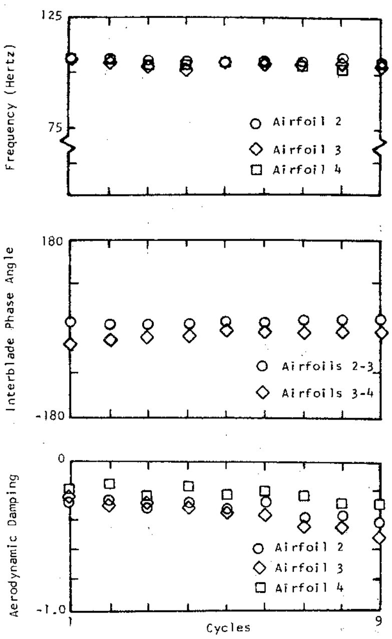

Fig. 10 Cycle-to-cycle variation in frequency, interblade phase angle, and aerodynamic damping at an inlet Mach number of 1.67 and a stagger angle of 66.09°.

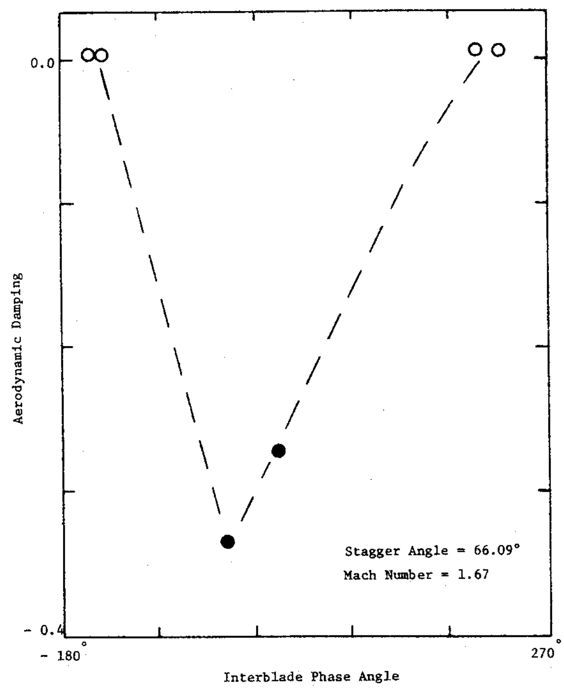

Fig. 11 Aerodynamic damping g vs interblade phase angle for a cascade stagger angle of 66.09° and inlet Mach number of 1.67.

correlation of the experimental data and the corresponding isolated airfoil theoretical results was quite good. The cantilevered airfoil cascade was then tested in the supersonic wind tunnel facility over an inlet Mach range of 1.4-1.7 following the test procedure previously described.

For an inlet Mach number of 1.60 and a 61.09° stagger angle, it was found that 180° interblade phase angle oscillations did not decay when the driving signals to the airfoils were stopped; i.e., the cascade was in a torsional flutter condition. Figure 7 shows the torsion bar mounted strain gage signals during this flutter digitized at the rate of 30,000 points per sec. Figure 8 presents the results of the on-line cycle-to-cycle analysis of this digitized data from the center 3 airfoils in the cascade to determine the torsional flutter frequency and the interblade phase angle as measured from the time at which the driving signals to the airfoils were stopped. As can be seen, this flutter is frequency locked with a small cycle-to-cycle variation in the interblade phase angle. Figure 9 presents a sequence of schlieren photographs of the time-dependent phenomena occurring during this flutter taken at 5000 frames per sec.

For an inlet Mach number value of 1.67 and a driving interblade phase angle of 90°, the 66.09° stagger angle cascade was found to be stable; i.e., the oscillations decayed with time. Figure 10 shows the results of the on-line cycle-to-cycle analysis of the digitized strain gage data from the center 3 airfoils in the cascade to determine the torsional frequency, the interblade phase angle, and the aerodynamic damping, respectively, as measured from the time the driving signals to the airfoils were stopped. As indicated, the cycle-to-cycle

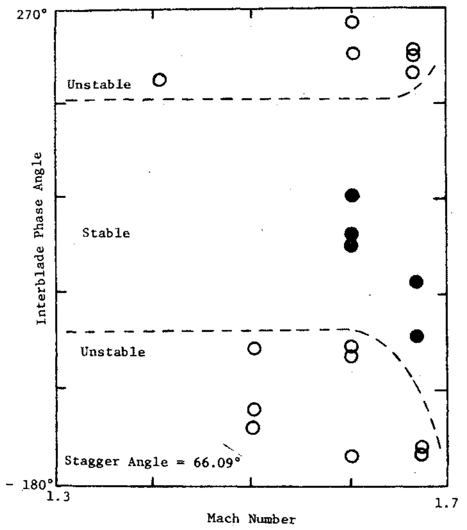

Fig. 12 Dependence of cascade stability on the interblade phase angle and Mach number for a 66.09° stagger angle.

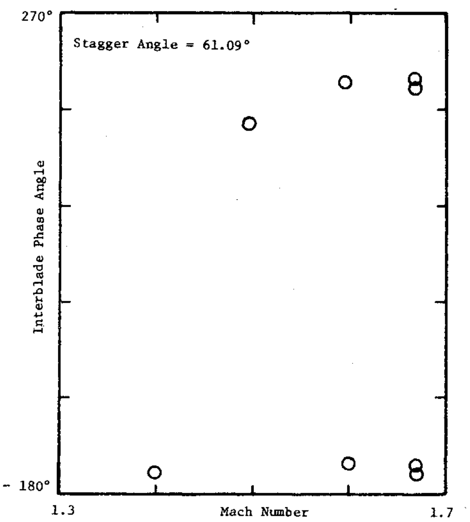

Fig. 13 Interblade phase angle vs cascade inlet Mach number for a 61.09° stagger angle.

variation in these quantities, and in particular the interblade phase angle, is relatively small.

Figure 11 clearly demonstrates the quantitative significance of the interblade phase angle on the dynamic aeroelastic characteristics of the airfoil cascade. This figure shows the variation of aerodynamic damping with interblade phase angle for a cascade stagger angle value of 66.09° and an inlet Mach number equal to 1.67. A nonnegative value for aerodynamic damping indicates that the cascade is unstable. Hence, the stability of the cascade is directly dependent on the value of the interblade phase angle; i.e., the cascade is stable at the previously described flow and geometric conditions for phase angle values in the region centered around 0, but is unstable for phase angles not in this region.

Figures 12 and 13 indicate the dependence of the cascade stability on the interblade phase angle and the cascade inlet Mach number for 66.09° and 61.09° stagger angles, respectively. Similar to Fig. 11, for the 66.09° stagger angle there is a region of interblade phase angle values wherein the cascade is stable and outside of which it is unstable. Thus, it can be clearly seen that the interblade phase angle is a significant parameter with regard to this torsional cascade instability.

The 66.09° stagger angle data presented in Fig. 12 indicates that both stable and unstable modes of operation occurred. However, at a stagger angle of 61.09° this cascade was always unstable with a phase angle near to 180° independent of the

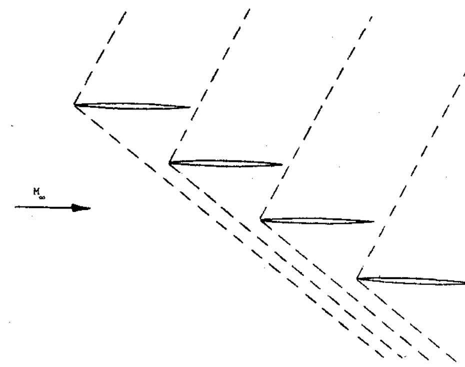

Fig. 14 Flow and geometry conditions such that only downstream interactions are possible.

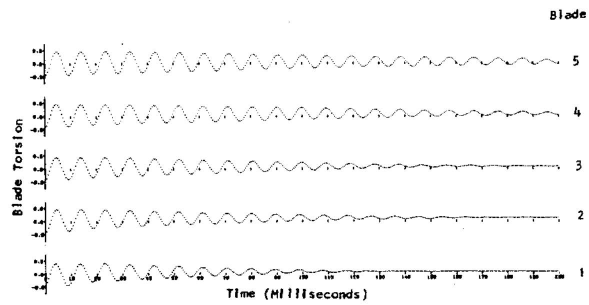

Fig. 15 Digitized strain gage signals for downstream airfoil interactions.

initial driving phase angle value, as indicated in Fig. 13. Hence, increasing the value of the stagger angle results in increased stability for the cascade.

For time-dependent supersonic inlet cascade flow with a subsonic axial component, as considered in this investigation, there are flow and geometry conditions which exist such that some airfoils in the cascade are more stable than others. The example of interest herein is the following.

For the higher values of the cascade inlet Mach number and stagger angle, the bow wave from the second airfoil does not intersect the first airfoil, the bow wave from the third airfoil does not intersect the second airfoil, etc. Hence, as indicated in Fig. 14, the time-dependent cascaded airfoil interactions can only occur in the downstream direction; i.e., as far as the first airfoil is concerned, it is an isolated airfoil—unaware of the presence of the rest of the cascade. However, the first airfoil may affect the other airfoils in the cascade by means of its right-running bow shock which determines the inlet condition to the second airfoil. Similarly, the second airfoil is only aware of the first airfoil, the third airfoil is only aware of the first and second airfoils, etc.

An isolated airfoil is stable for all frequencies at inlet Mach number values greater than approximately 1.58. Hence, for the case of interest where the Mach number = 1.67, when the computer stops driving the electromagnets, the oscillations of the first airfoil rapidly decay. The second airfoil then sees a steady inlet and also acts as an isolated airfoil with its oscillation decaying rapidly. This continues down the cascade until all of the airfoil oscillations have decayed in turn. This phenomenon is clearly demonstrated in Fig. 15.

VII. Summary

A unique supersonic inlet time-dependent cascade experimental technique has been described wherein 2 laboratory-size digital computers and an electromagnetic cascade excitation mechanism are used to simulate the time-dependent airfoil interactions. These computers are also used to acquire and analyze on-line the resulting time-dependent torsion bar mounted strain gage data. Experimental results from a single airfoil test were compared to supersonic isolated airfoil theoretical results and good agreement obtained. Digitized time-dependent data obtained during the cascade testing and analyzed on-line were presented which show the cycle-to-cycle variation in: a) torsional frequency, interblade phase angle and aerodynamic damping for stable operating conditions; and b) torsional frequency and interblade phase angle for unstable operating conditions (flutter).

The experiment described herein quantitatively indicates the significance of the cascade inlet Mach number, cascade stagger angle and, in particular, the interblade phase angle on the flutter characteristics of cascaded airfoils. Also, this experiment has demonstrated an appropriate means of simulating the time-dependent airfoil interactions which occur in a supersonic inlet flowfield with a subsonic axial component.

References

[1] Kurosaka, M., "On the Unsteady Supersonic Cascade with a Subsonic Leading Edge—An Exact First Order Theory—Part 1," ASME Paper 73-GT-15, 1973.

[2] Kurosaka, M., "On the Unsteady Supersonic Cascade with a Subsonic Leading Edge—An Exact First Order Theory—Pt. 2," ASME Paper 73-GT-16, 1973.

[3] Verdon, J. M., "The Unsteady Aerodynamics of a Finite Supersonic Cascade with Subsonic Axial Flow," ASME Paper 73-APMW-6, 1973.

[4] Brix, C. W. and Platzer, M. F., "Theoretical Investigation of Supersonic Flow Past Oscillating Cascades with Subsonic Leading-Edge Locus," AIAA Paper 74-14, Washington, D.C., 1974.

[5] Fleeter, S., "On the Unstalled Subsonic, Sonic, and Supersonic Aerodynamic Coefficients Necessary for Aeroelastic Calculations," *Aeroelasticity in Turbomachines—Proceedings of a Project SQUID Workshop Held at Detroil Diesel Allison,* General Motors Corp., June 1972.

[6] Platzer, M. F. and Chalkley, H. G., "Theoretical Investigation of Supersonic Cascade Flutter and Related Interference Problems," AIAA Paper 72-377, San Antonio, Texas, 1972.

[7] Fleeter, S., Ed., "Aeroelasticity in Turbomachines," *Proceedings of a Project SQUID Workshop Held at Detroil Diesel Allison,* General Motors Corp., June 1972.

[8] Holtman, R. L., Huffman, G. D., McClure, R. B., and Sinnet, G. T., "Test of a Supersonic Compressor Cascade," Rept. 72-0170, Dec. 1972, Aerospace Research Labs., Wright-Patterson Air Force Base, Ohio.

[9] McClure, R. B., Huffman, G. D., Holtman, R. L., and Sinnet, G. T., "A Comparison of Four Supersonic Compressor Cascades for Use in the High Flow Compressor," RN 72-89, Detroil Diesel Allison, General Motors Corp., Indianapolis, Ind., to be published.

[10] Tramm, P. C. and Huffman, G. D., "Airfoil Design for High Tip Speed Compressors," *Journal of Aircraft,* Vol. 11, Nov. 1974, Nov. 1973, pp. 682-689.

[11] Synder, L. E. and Commerford, G. L., "Supersonic Unstalled Flutter in Fan Rotors; Analytical and Experimental Results," ASME Paper 74-GT-40.