Application of Digital Fourier Analysis in Processing Dynamic Aerodynamic Heating Measurements

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Abstract

A PRACTICAL application of a digital Fourier analysis (fast Fourier transform) in processing fluctuating heat-transfer data was utilized in a wind-tunnel test program at Mach number 8. A 4-deg, half-angle cone instrumented with conventional heat gages was oscillated in pitch at an amplitude of 2 deg and frequencies up to 15 Hz. The gages had a time constant of approximately 120 ms, which was not sufficiently responsive to follow the motion, and the Fourier analysis was used to correct the gage outputs. These measurements were used to map the location of the boundary-layer transition front.

The purpose of this paper is to describe in some detail the technique used in processing these transient heat-transfer measurements. A more detailed presentation may be found in Ref. 1. The results indicate that the Fourier analysis was a very powerful method for correcting dynamic heat-transfer measurements.

Contents

The procedure for analyzing transient sensor data signals which are produced by undefined input signals is well documented. Any transient signal can be viewed in the frequency domain as a spectrum (amplitude distribution of the real and imaginary terms as a function of frequency), and the fast Fourier transform (FFT) algorithm provides the numerical procedure needed to transform digitally recorded transient data from the time domain into the frequency domain. Brigham[2] has suggested that the FFT, in many respects, is analogous to using natural (or common) logarithms as a means of substituting simple arithmetic operations such as addition and subtraction for multiplication and division. In the frequency domain, certain numerical operations on a signal such as convolutions, correlations, energy content, and discrete digital filtering can be performed quite simply. In particular, the FFT can be used to determine the response or transfer function of a linear measuring system based on the distorted output of a sensor along with the known calibration pulse which caused the sensor response. A computer calculates the Fourier transforms of both the input and output time histories and ratios the two transforms to obtain the transfer function of the sensor.

When a transient of the sensor is recorded, the distorted output is digitized, transformed into the frequency domain using the FFT, and multiplied by the previously calculated sensor transfer function. This process produces a frequency-domain version of the unknown input signal from which sensor distortion has been removed. Transformation back into the time domain will now reproduce the unknown input signal, theoretically free of distortion.

Two types of heat sensors were evaluated in this development study. The primary sensor was a thermopile Gardon gage which is a heat flux sensor with a nominal output of 1.0 mV/[Btu/(ft^2-s)] and a response time of 120 ms. The second sensor was a temperature sensor which was used in conjunction with a properly designed analog circuit to produce an output which was proportional to the heat flux imposed on the sensor (no results for this sensor are presented in this synoptic). The gages were statically calibrated to determine their scale factors {[Btu/(ft^2-s)]/mV}. In addition to these static calibrations, a dynamic calibration provided the transfer function of the gage. The techniques which were used to obtain the calibrations and gage transfer functions are presented in Ref. 1.

A practical application of the use of digital Fourier analysis in processing fluctuating heat-transfer data was utilized in a wind-tunnel investigation. This numerical technique was used to correct for the time response (or to infer the input) of the heat gages which were flush mounted on an oscillating cone.

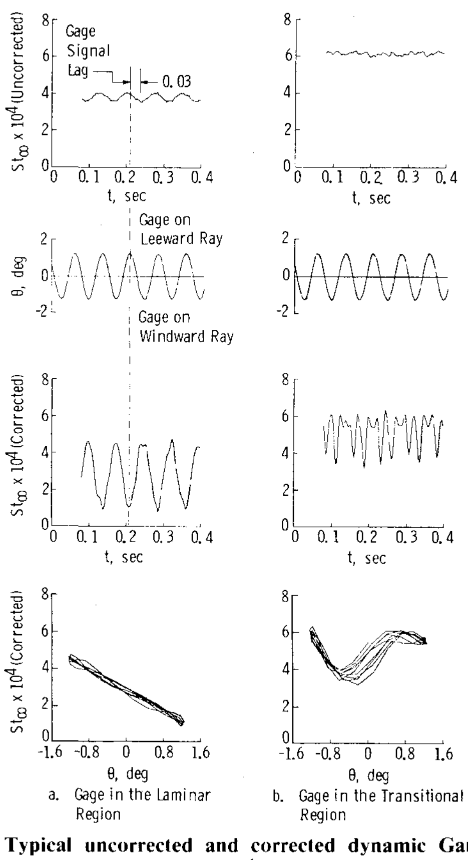

Fig. 1 Typical uncorrected and corrected dynamic Gardon gage results, $\omega = 13.6$ Hz, $Re_\infty = 3.7 \times 10^6$/ft.

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Index categories: Experimental Methods of Diagnostics; Boundary-Layer Stability and Transition; Entry Vehicle Testing, Flight and Ground.

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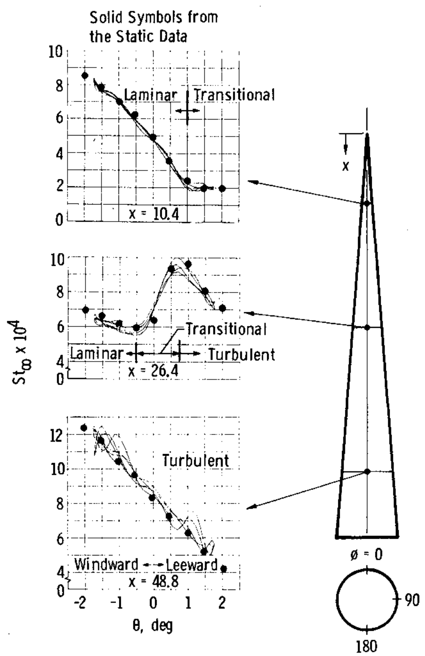

Fig. 2 Dynamic heat-transfer data on a sharp cone, $\omega = 5$ Hz, $Re_\infty = 1.7 \times 10^6$/ft, $\phi = 0$.

This motion of the cone caused the boundary-layer-transition front on the cone to translate along the body with cone attitude, and the instantaneous location of the transition front was detected from the heat-transfer distribution along the cone surface.

Some typical dynamic heat-transfer results are presented in Fig. 1. The results are representative of the various gage output signals and of the effect of the gage transfer function on the output signal. The presented results include time t, the model oscillation angle θ, and the uncorrected and corrected gage output signals in terms of Stanton number St_∞. The results were obtained at a model oscillation frequency ω of 13.6 Hz and a freestream Reynolds number Re_∞ of 3.7×10^6 ft^{-1}. In Fig. 1a, the results for a Gardon gage located in the laminar region are presented. The results show that the gage signal lagged the model oscillation angle θ by approximately 0.03 s. Applying the transfer function corrected this lag and increased the amplitude of the gage variations. When the Stanton number was plotted as a function of the oscillation angle, a linear variation was produced as expected. The results for a Gardon gage located in the transition region are presented in Fig. 1b. The gage output signal (uncorrected) does not appear to show any tangible variations with respect to the oscillation angle. However, after applying the transfer function and plotting the results as a function of the oscillation angle, meaningful results are obtained.

Dynamic heat-transfer results for the sharp cone along the 0-deg ray are presented in Fig. 2. For the gage that is located in a turbulent region ($x = 48.8$ in.), the variation of Stanton number is linear with pitch angle θ, as expected. This linear variation is also obvious in other gages that were located closer to the model nose. If a sharp break from the linear curve in the St_∞ variation occurs, it is clearly the end of transition. Similarly, a gage which is located in a laminar region ($x = 10.4$ in.) will also indicate a linear variation with θ, and as transition moves over the gage, the slope will change. The beginning and end of transition are clearly indicated by a gage that encounters both a laminar and a turbulent boundary layer ($x = 26.4$ in.). The solid symbols which are presented in the figure were obtained from the static data ($\omega = 0$) and are in excellent agreement with dynamic results.

The results show that this technique involving the use of the FFT is a very powerful tool for correcting dynamic heat-transfer measurements obtained from conventional heat gages.

Acknowledgment

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References

[1] Jenke, L. M. and Strike, W. T., "Application of Digital Fourier Analysis in Processing Heat-Transfer Measurements on an Oscillating Cone in a Hypersonic Stream," AIAA Paper 78-778, San Diego, Calif., April 19-21, 1978.

[2] Brigham, E. O., *The Fast Fourier Transform*, Prentice-Hall, Englewood Cliffs, N. J., 1974.