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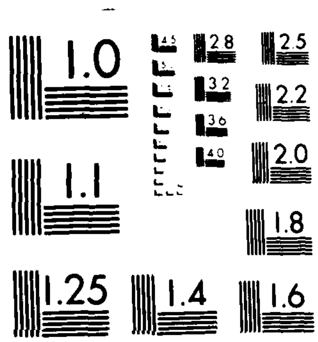

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Unsteady Swirling Flows in Gas Turbines

Final Technical Report

Contract F49620-78-C-0045

By: M. Kurosaka
University of Tennessee Space Institute

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SWIRLING FLOW	STEADY AERODYNAMICS
FLOW-INDUCED OSCILLATION	'VORTEX WHISTLE'
FATIGUE FAILURE	RANQUE-HILSCH EFFECT

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of the program was to acquire fundamental understanding of a phenomenon characterized by violent fluctuations occuring in swirling flows in gas turbines; this instability, dubbed here as the "Vortex Whistle" is known to be capable of causing fatigue failures in gas turbine components. Although the phenomena of the 'Vortex Whistle' have never remained unrecognized, perhaps for the reason that they appeared in seemingly unrelated incidents under various disguise, no comprehensive investigation appears to have been embarked upon. In addition, in spite of the fact that the vortex whistle is a pure tone noise and distinctly

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audible, its role as a source of the aircraft engine noise has never been recognized. Most important, when the vortex whistle becomes intense, it induces a change in the steady flow field, the total temperature being spontaneously separated in the radial direction (the Ranque-Hilsch effect). Not only its implications to the steady aero design of turbomachines are of obvious importance, but also this appears to offer an unmistakable clue to the puzzling Ranque-Hilsch effect.

In this program, the problem was formulated as the study of unsteady disturbances in swirling flows present within a cylindrical or co-annular duct; both the theoretical and experimental investigations were conducted. The frequency of the unsteady disturbances predicted by the theory was found to agree well with the experimental results.

Futhermore, the nonlinear analysis led to the prediction that the intense disturbances can deform the radial velocity distribution into a forced vortex, resulting in the radial separation of total temperature. This was confirmed by experiments, where by suppressing the vortex whistle at a tuned frequency, the radial separation of total temperature (the Ranque-Hilsch effect) was found to diminish to a large extent.

Unsteady Swirling Flows in Gas Turbines

Final Technical Report

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Washington, D. C. 20332

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Tullahoma, Tennessee 37388
March, 1983

TABLE OF CONTENTS

1. *Program Objectives* . . . 1
2. *Features of 'vortex whistle' Phenomenon* . . . 1
3. *Significant Achievements* . . . 3
4. *Implication of the Present Program as Related to Aircraft Gas Turbines* . . . 4
5. *References* . . . 5
6. *Cumulative List of Publications* . . . 5
7. *Oral Presentations* . . . 6
8. *Advanced Degrees Awarded in Connection with the Research Efforts* . . . 6

1. *Program Objectives*

The overall objective was to acquire fundamental understanding of phenomena characterized by violent fluctuation induced by swirling flow – the 'vortex whistle', *often found to occur in various* aircraft engine components. By conducting a comprehensive and systematic investigation into the 'vortex whistle', it was intended to achieve the following specific goals:

(1) by performing analysis to predict the frequency of the vortex whistle and verifying it against the experimental results, one can detune the natural frequencies of engine components away from it in order to ensure their structural integrity, and

(2) by appealing to the mechanism of acoustic streaming induced by the vortex whistle, we explained, through both analysis and experiment, the transformation of steady radial profile – in particular the total temperature separation or the Ranque-Hilsch tube effect; the implications of this are that the radial distortion of the flow field may have strong bearing on the 'steady' aero data obtained in the swirling flow environment of gas turbines.

2. *Features of 'vortex whistle' Phenomenon*

"Vortex whistle" — this is the sobriquet we use in this report to describe one of the treacherous flow-induced vibration phenomena encountered in gas turbines. It is a spontaneous violent fluctuation that occurs in any swirling flow – including, but not necessarily restricted to, gas turbines. When the vortex whistle does occur in gas turbines, the induced vibration can sometimes become so severe that the blades and other structural members suffer serious damage. In addition to its obvious implications related to aeroelastic problems, its significance as a potential source of engine noise appears to have received scant, if any, attention and merits serious consideration. More important, experimental evidences to be recounted shortly disclose the unsuspected fact that the vortex whistle can metamorphose the very steady flow field, both in velocity and temperature distribution; that is, fluctuating, unsteady (a.c.) components of flow somehow interact with the time-averaged, mean (d.c.) components and alter them. The implications of this are obvious in raising serious questions about interpreting what was presumed to be 'steady' data in compressors and turbines; in addition, beyond the confines of turbomachinery technology, they yield a clue to explain the dimly foreseen mechanism of energy separation in swirling flow, the so-called Ranque-Hilsch tube effects.[1,2]

Vortex whistle can be characterized by the following key features. First, it is induced by the presence of a strong swirl. Second, it is a pure tone noise and its frequency increases proportionately to the flow-rate or swirl. It turns out that the presence of such rotating surfaces as rotor blades is not really necessary to produce the vortex whistle. The whistle can be found even in the swirl created by the tangential injection to a stationary cylinder. Historically it was, in fact, in this arrangement where Vonnegut[3] first discovered, in the swirling flow, the presence of a pure tone noise whose frequency increases proportionately to the flow rate. Because of the continuous change in frequency, he found that one can play musical tunes by varying the blowing pressure by mouth. It was Vonnegut who coined the name vortex whistle for this musical instrument and it is due to this reason that we call the similar descrete tone in swirling flow by this term. (For other earlier investigations, see Michelson[4], Suzuki[5] and Chanaud[6,7].) What elicits our extreme interest in the present context is the highly suggestive circumstances where Vonnegut was led to his finding of the vortex whistle – he discovered it while working on the application of the Ranque-Hilsch tube effect[8].

In gas turbines, the vortex whistle is known to occur in various components such as in the downstream section of inlet guide vanes of radial flow duct, a ring chamber[9], and turbine colling air cavity. Instances are known where the vortex whistle in the swirling flow of cooling air cavity seriously jeopardized the structural integrity of turbines.

Recently, the problem of the vortex whistle has unexpectedly presented itself in the test rig called an annular cascade built by the General Electric Company, Evendale, Ohio under the USAF sponsorship to investigate some flutter characteristics of compressor blades in the non-rotating environment[10,11,12]. As a whole, the annular cascade is in the shape of a stationary duct formed between inner and outer casings; swirling air created by the variable vanes enters the test section, where the test cascade airfoils are nominally mounted on the outer casings. The whistle revealed itself in the check-out phase of the annular cascade and its presence was detected even after the removal of the test airfoils; the frequency of the whistle was found to increase almost proportionately to the flow rate. The dynamic fluctuation was so intense as to endanger the subsequent test of bladings. Hence, dynamic measurements of the whistle have been carried out to seek a means to suppress the whistle. Based upon this, the cascade was installed with acoustic suppressors and the unacceptable dynamic flow disturbance was finally removed. Since then, the vehicle has successfully been in use for aeroelastic purposes and served to identify some important aspects of flutter[12].

Although the problematical vortex whistle has been eliminated from the annular cascade, the measurements made at a time when the whistle was still present offers us an opportunity to examine this unsteady phenomena in some detail. In addition to the observed increase of frequency proportional to the flow rate, the data, taken when the test airfoils were removed, reveals the following unexpected change in the steady or time-averaged flow field. When the whistle was inaudible, the steady-state tangential velocity distribution in the radial direction was in the form of a free vortex; the steady-state temperature was uniform. However, when the whistle became intense, then above a certain swirl, the tangential velocity near the inner wall became, aruptly and considerably, reduced, the radial profile transformed from a free vortex into one somewhat similar to a forced vortex; furthermore, what is utterly surprising is that the total temperature, initially uniform at the inlet, spontaneously separated into a hotter stream near the outer wall and a colder one near the inner wall, with the difference as large as 35°F. This latter vividly reminds us of the Ranque-Hilsch effect(1,2). Take note of the fact that, upon the installation of the acoustic suppressors, which had succeeded in eliminating the vortex whistle, the deformation in the radial profiles of velocity and temperature vanished.

Besides these observations recorded in the annular cascade, additional incidents observed in the other test rig disclosed much the same phenomenon. In a radial in-flow test rig of Detroit Diesel Allison, Indianapolis, Indiana, the vortex whistle, apparently induced by the swirl created downstream of inlet guide vanes, was detected beyond a certain flow rate; corresponding to the initiation of the sound, the total pressure, measured at a certain traverse point downstream of the inlet guide vanes, exceeded its upstream incoming value and at the same time, the exhaust pipe became noticeably warm when touched by a hand, while the formation of ice was detected on the surface of the back-plate at a location corresponding to the centerline of the pipe; furthermore, the maximum Mach number and mass flow was considerably lower than expected. The installation of the acoustic suppressor eliminated, as before, these anomalous effects and resulted in increasing the maximum Mach number and flow by 30%.

In these, the acoustic streaming(13), or the d.c. components induced by the periodic disturbances, did somehow distort the steady flow field.

3. *Significant Achievements*

In this section, the results of the analytical investigation are discussed first, followed by the description of the experimental data.

The linearized form of the periodic disturbances was assumed to be a helically advancing wave with wave numbers specified in both the axial and tangential direction; these constitute the leading terms of unsteady flow field. The fundamental frequency of periodic disturbances were determined by solving the linearized governing equation. In addition, the second order terms, whose time-averaged components generate acoustic streaming and other higher order terms, were studied systematically by applying the method of the matched asymptotic expansion to the full compressible and unsteady Navier-Stokes equations.

The results of the linearized analysis showed that the frequency increases nearly proportionately to swirl, both for a swirling flow within a co-annular duct and a single pipe; this linearity is one of the key features of vortex whistle, as already pointed out.

With regard to the acoustic streaming in a pipe where the base flow was assumed to be of Rankine vortex, the tangential streaming near the tube periphery was found to become infinitely large for the first tangential mode ($m = 1$ mode) and this remains so regardless of the magnitude of the base swirl. If and when such a disturbance is excited, this tends to deform the base Rankine vortex into a forced vortex. The flow with the initially uniform total temperature becomes separated radially into a hotter gas near the tube periphery and a colder one near the center. This is none other than the Ranque-Hilsch effect.

The predictions were confirmed by experiments. First, the calculated frequency was found to agree closely with the measured data of the vortex whistle (Figure 1). Second, the pivotal point that the vortex whistle does cause the temperature separation, indicated by theory, was confirmed by the following test: on the Ranque-Hilsch tube of 11/16 inches in diameter, we installed acoustic suppressors of organ-pipe type (Figure 2 and 3), tunable to the fundamental frequency of the vortex whistle, corresponding to the first tangential mode $m = 1$. We thus attenuated the intensity of the vortex whistle at a tuned frequency, confirmed that this induced the reduction of its second harmonic and most important, verified that this did indeed reduce the total temperature separation. Figures 9-13 of Ref. 6 of Section 6, display such results. For instance, in the attached Figure 4 the acoustic suppressor was tuned to 4KHz; at the moment when the fundamental frequency of the vortex whistle reached the tuned frequency, its level plummeted abruptly by 25dB, which in turn reduced its second harmonic by 14dB. At this instant, the cold temperature at the tube centerline, which had gone down as low as -31°F immediately jumped to 30°F – with a temperature rise equal to 61°F. The changes in the frequency spectra are shown in Figure 5.

The small size of the main tube, with the diameter of 11/16 inches, prevented the detailed radial survey of flow field. Therefore, an up-scale verion of the test rig was built subsequently; the diameter of the new main tube was now 2 inches, approximately 3 times larger than the previous one.

The results obtained from the up-scaled version not only confirmed the data from the smaller test rig but also showed that, at the instant of sound suppression, the total temperature near the periphery took a sudden plunge of 10°F, as expected from the balance of thermal energy.

4. *Implication of the Present Program as Related to Aircraft Gas Turbines*

The potential applications of the program to the aircraft engine technology are as follows:

(a) By the explicit recognition of the dependence of the vortex whistle upon the governing parameters as found in the present investigations, it is possible to avoid the structural failure of aircraft engines by detuning the natural frequency of various engine components away from the descrete frequency.

(b) By being cognizant of the acoustic characteristics of the vortex whistle, one can conduct diagnosis of the engine noise and identify the vortex whistle out of the other pure tone noise; this will aid in the effective noise suppression.

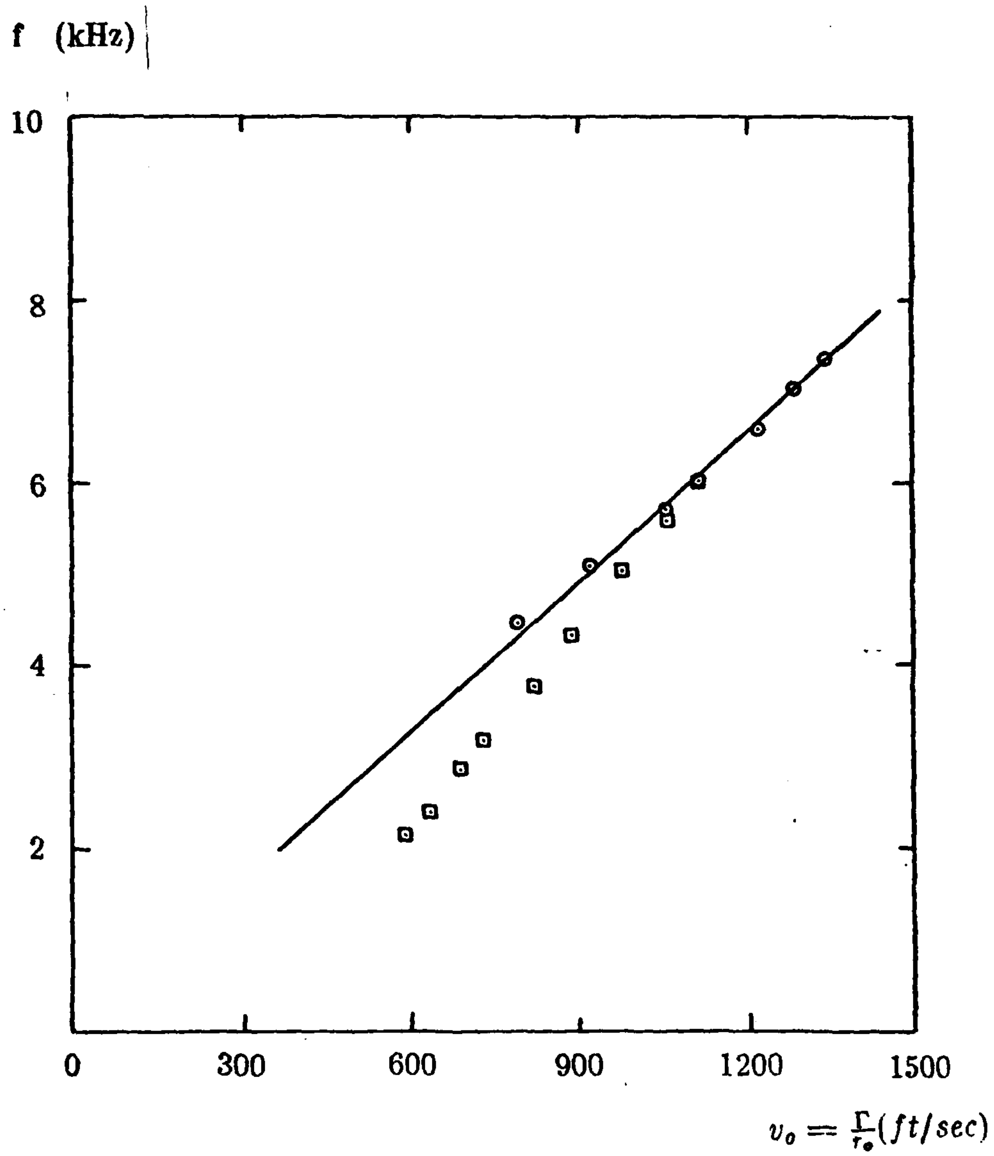

Figure 1. Fundamental frequency for solid main tube.
——— calculated; ⊡ , L = 1.65 in.; ⊙ , L = 0.5 in.
(Taken from Figure 6, Ref. 6, Section 6.)

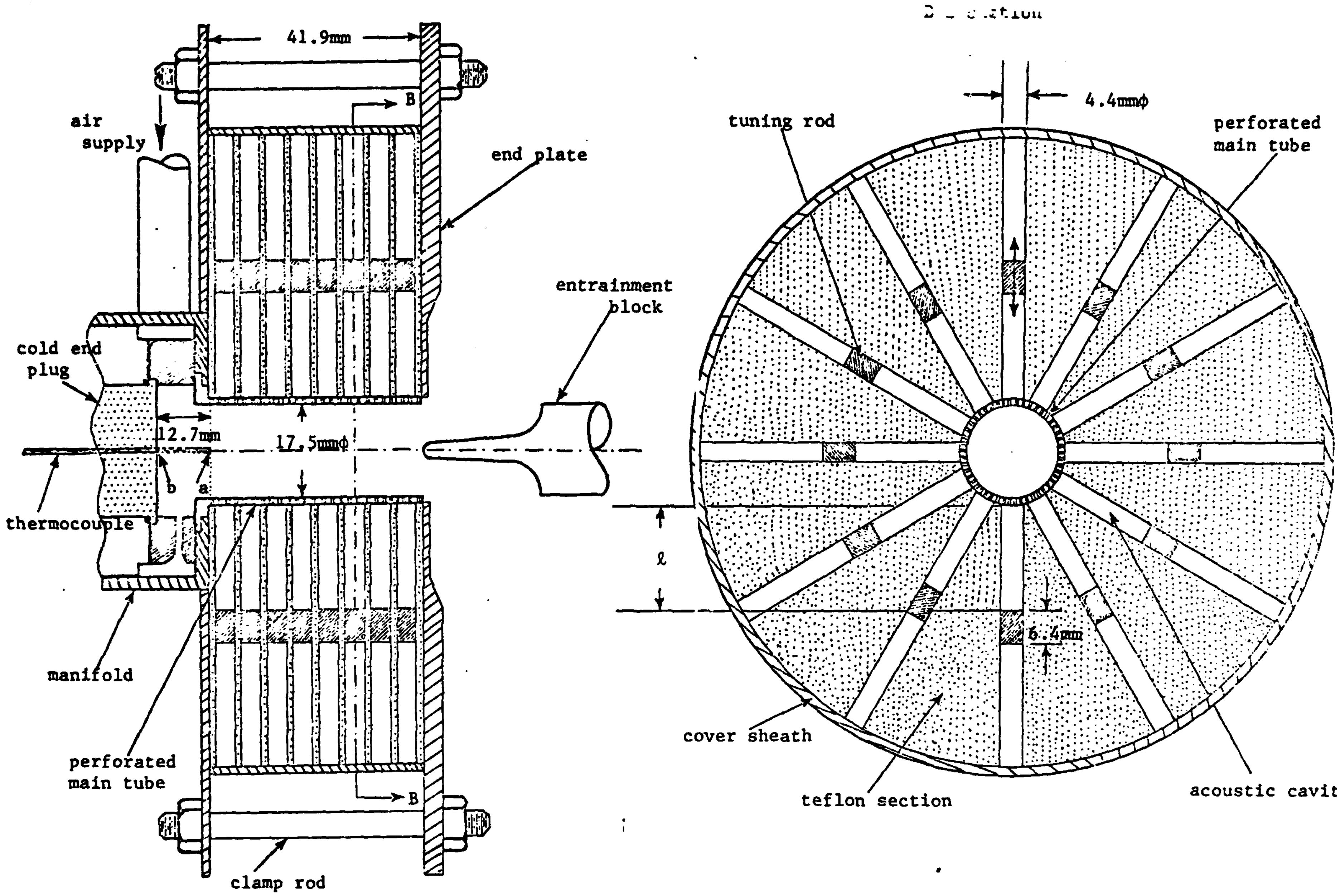

Figure 2. Layout of vortex-flow test rig: perforated main tube with acoustic suppressors.

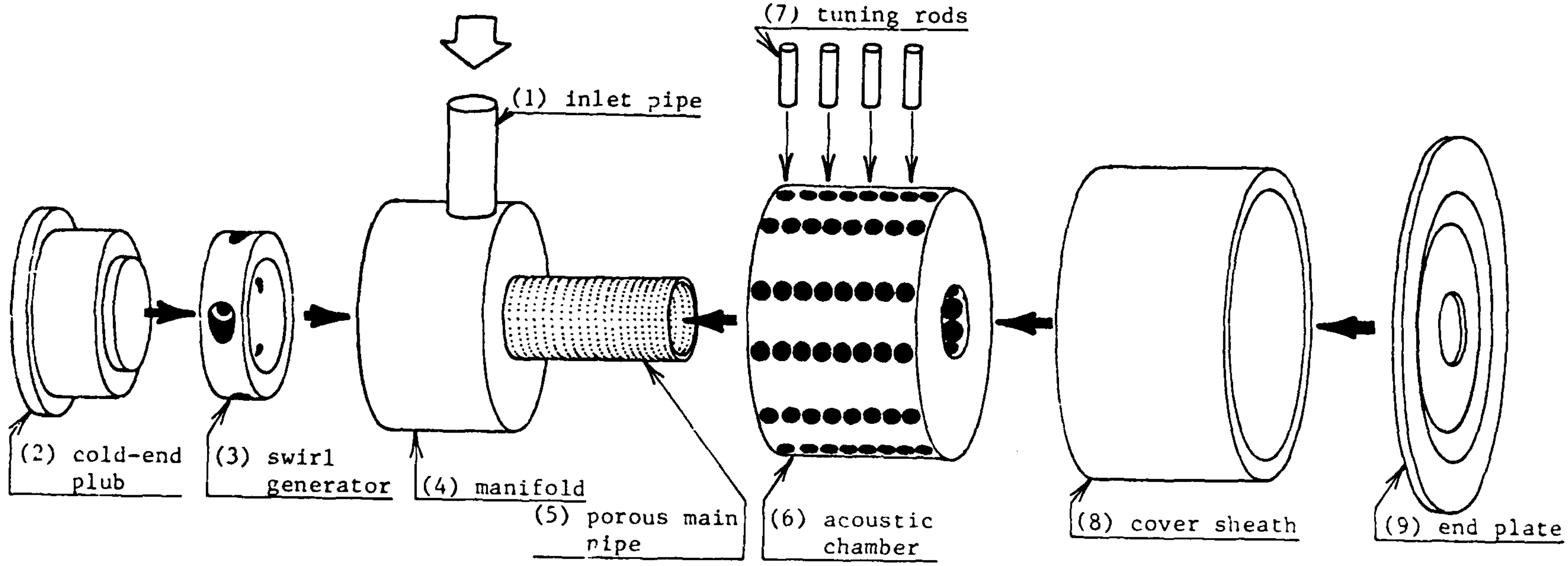

Figure 3. Exploded view of vortex-flow test rig.

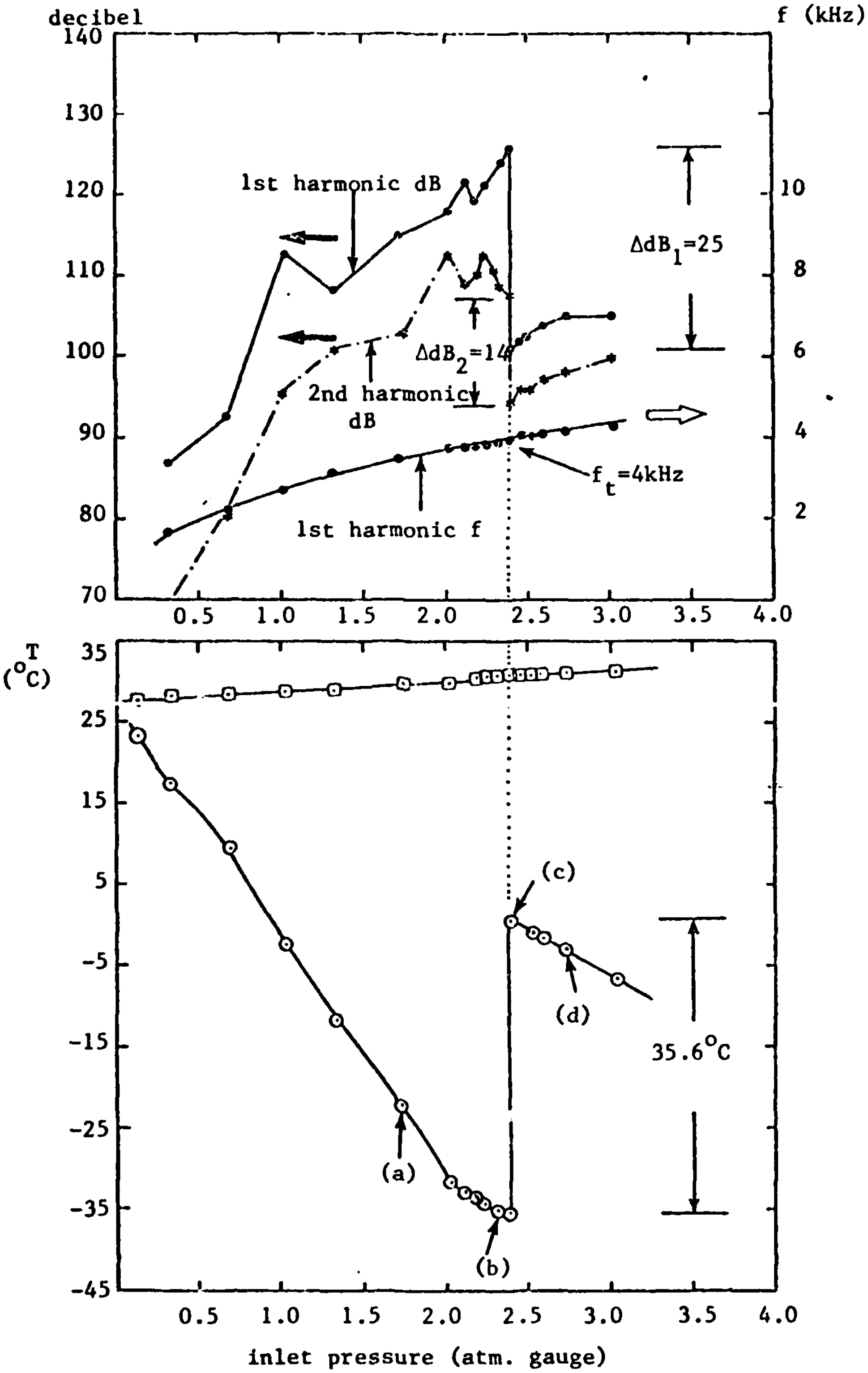

Figure 4. Temperature and acoustic measurement for perforated main tube with acoustic suppressors. ℓ = 1.02 cm; ⊡ inlet temperature; ⊙ centerline temperature (a), (b), (c) and (d) correspond to those of Figure 5. (Taken from Figure 9, Ref. 6, Section 6.)

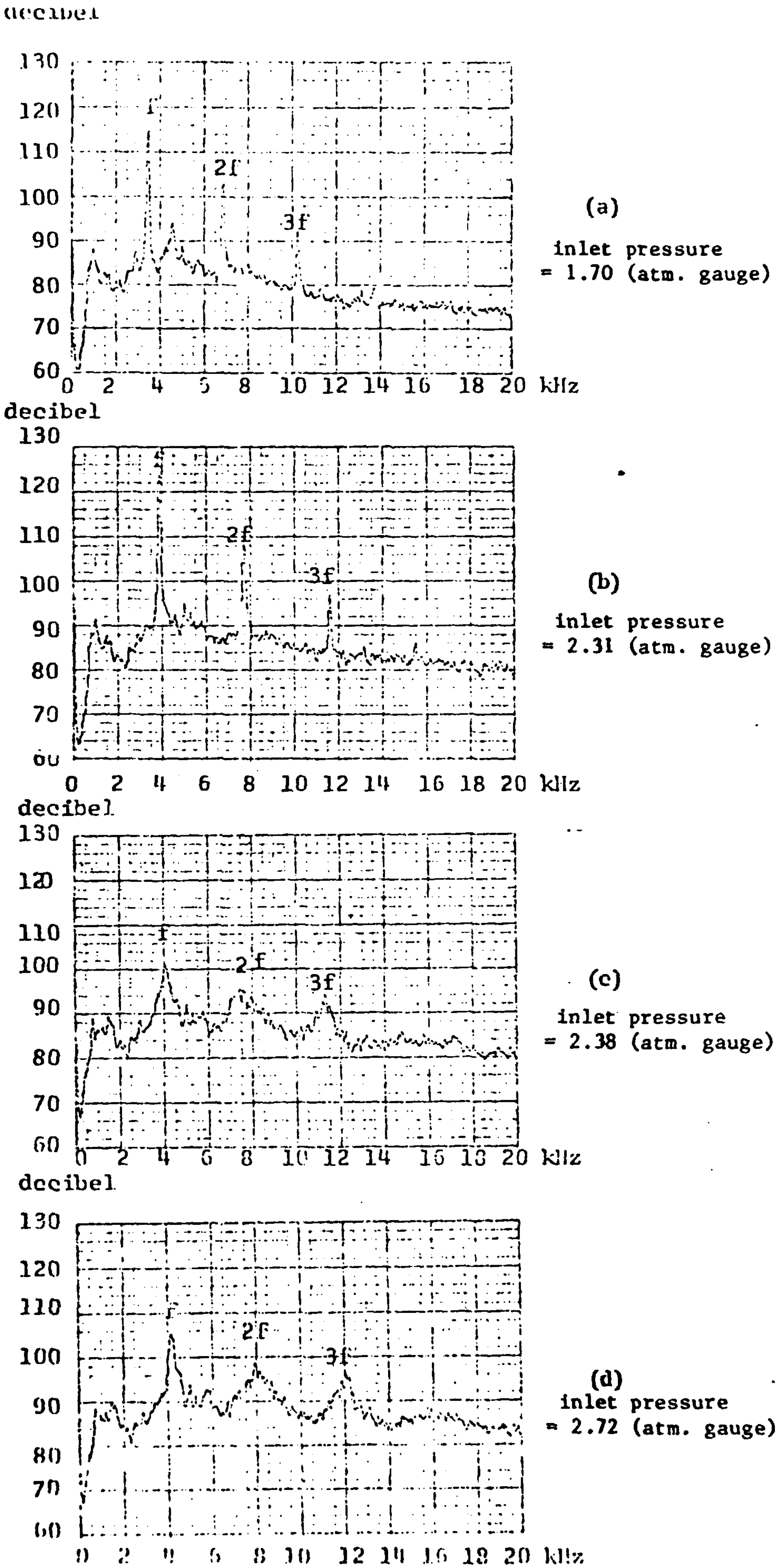

Figure 5.

Frequency spectra for perforated main tube with acoustic suppressors. ℓ = 1.02 cm.

(c) The deformation of steady flow field induced by the vortex whistle implies that in the steady aerodynamic design of rotors/stators and in interpreting the steady data, due consideration may have to be given to this acoustic streaming effect.

(d) The positive exploitation of the vortex whistle and the induced temperature separation to enhance the turbine cooling may lead to the reduction of specific fuel consumption.

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6. Cumulative List of Publications

(1) Kurosaka, M., "Linear and Non-Linear Analysis of 'Vortex Whistle' - Another Blade Buster," *Proceedings of the 2nd Symposium on Aeroelasticity in Turbomahinces, sponsored by International Union of Theoretical and Applied Mechanics, held in Lausanne, Switzerland, Sept. 8-12, 1980, pp. 443-453, Juris-Verlag, Zurich.*

(2) Kurosaka, M., "Vortex Whistle: An Unsteady Phenomenon in Swirling Flow and its Effect on Steady Flow Field," AIAA paper, 81-0212, presented at AIAA 19th Aerospace Sciences Meeting, January, 1981, St. Louis.

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(6) Kurosaka, M., "Acoustic Streaming in Swirling Flow and the Ranque-Hilsch (vortex-tube) Effect", *Journal of Fluid Mechanics, Vol. 124, 1982, pp. 139-172.*

(7) Kurosaka, M. Goodman, J. R., Chu, J. Q. and Kuroda, H., "An Interplay Between Acoustic Waves and Steady Vortical Flows", AIAA paper 83-0740, to be presented at AIAA 8th Aeroacoustics Conference, April, 1983, Atlanta.

7. Oral Presentations

In addition to the spoken papers, Ref. 1, 2, 3, 4, 5 and 7 of Section 6, the following oral presentations have been made.

- "Linear and Non-Linear Analysis of 'Vortex Whistle' - Another Blade Buster", presented at Aachen Technical University, West Germany, September, 1980.
- "Vortex Whistle - An Unsteady Phenomenon in Swirling Flow in Turbomachinery and its Implications" presented at joint NASA, AF/Navy Symposium on Aeroelasticity of Turbine Engines, NASA Lewis Research Center, Cleveland, OH, October 27-29, 1980.
- "Vortex Whistle" a second C. E. Danforth lecture on Airbreathing Propulsion, University of Cincinnati, November 17, 1980; also AiResearch Manufacturing Company, Pheonix, AZ, December 23, 1980; Detroit Diesel Allison, Indianapolis, Indiana, April 10, 1981; University of California at Los Angeles, September 30, 1981; Peking Institute of Aeronautics and Astronautics, October 14, 1981; University of Tokyo, Nov. 29, 1981; Wright-Patterson AFB, January 18, 1982; General Electric Company, Evandale, OH, January 19, 1982.
- "Acoustic Streaming as a Mechanism of the Ranque-Hilsch Effect", presented as a seminar at California Institute of Technology, January 18, 1983.

8. Advanced Degrees Awarded in Connection with the Research Efforts

- J. Q. Chu, "Some Allied Problems Related to Unsteady Flow, Part II: Acoustic Waves in Cylindrical Co-Annular Duct in the Presence of Free Vortex Swirl and Axial Flow", M.S. Degree, The University of Tennessee, June, 1979.
- J. M. McGee, "An Investigation of Unsteady Disturbances in Swirling Flows in an Annulus", M.S. Degree, The University of Tennessee, December, 1981.
- J. Q. Chu, "Acoustic Streaming as a Mechanism of The Ranque-Hilsch Effect", PhD. Degree, The University of Tennessee, November, 1982.