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THERMO-FLUID MECHANIC STUDY OF THERMOACOUSTIC DEVICES

Summary Report for the Period 1 June 95 to 31 May 96

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Abstract

The work is articulated in three separate projects: (*a*) development and study of a simplified model of thermoacoustic devices; (*b*) visualization of oscillating temperature and flow fields; (*c*) numerical modeling. The progress accomplished in the three areas is briefly reviewed.

The work carried out under this grant is articulated in three separate projects as follows:

1. Simplified model of thermoacoustic devices (A. Prosperetti)
2. Experimental effort: Visualization of oscillating temperature and flow fields (C. Herman)
3. Numerical modeling effort (O. Knio)

Brief description of projects

Project 1. The only theory presently available for the analysis of thermoacoustic devices is formulated in the frequency domain and is only applicable in the linear regime. Its extension to the nonlinear case appears to be formidable and it is likely that nothing short of fully numerical simulations will be available for a quantitatively accurate application to large-amplitude pressure oscillations. For this reason, an approximate, but much more manageable model, might be useful both as an exploratory tool and as a design guide. The project consists in the development of such a model.

Project 2. One reason that the performance of thermoacoustic refrigerators and engines has difficulties achieving the efficiency of the conventional commercially available units, is the poor performance of the heat exchangers in such devices. To improve their performance, it is essential to gain a better insight into the thermoacoustic heat transfer process. So far neither analytical nor numerical models are available to accurately predict the performance of heat exchangers in thermoacoustic devices. Therefore, the goal of the project is to quantify experimentally the heat transfer between the stack, the gas, and the heat exchangers.

Project 3. Analysis and prediction of the behavior of thermoacoustic devices have so far relied primarily on a linearized theory based on simplified quasi-one-dimensional flow models. In order to overcome these restrictions, this effort aims at (1) the development of a computational methodology for the simulation of the non-linear multi-dimensional flow within thermoacoustic stacks and heat exchangers, and (2) the implementation of the resulting numerical schemes to analyze the fundamental response of the flow within critical components and to quantify the performance of the device. The computational model development complements parallel efforts aiming at gaining detailed fundamental understanding of thermoacoustic devices through improved analytical models and laboratory experiments.

Approach

Project 1. By integrating the conservation equations for mass, momentum, and energy over the cross section of the thermoacoustic device, a quasi-one-dimensional mathematical model has been derived. The model is exactly identical with the well known theory of Rott in the linear case, but it has the advantage of extendable to a time-domain formulation and into the non-linear regime. While these extensions are not exact, the model is nevertheless useful to explore different design considerations such as the effect of the cross sectional area, the position of the stack, and many others.

Project 2. By applying experimental visualization techniques, such as holographic interferometry, smoke visualization, and thermochromatic liquid crystals to a thermoacoustic refrigerator model, we are able to visualize the oscillating flow and temperature fields in the stack region and its neighborhood. Understanding these heat transfer and flow phenomena is a first step towards a quantitative evaluation of the thermoacoustic heat transfer in the heat exchangers. In particular holographic interferometry, combined with high speed cinematography, provides a unique tool to quantify the unsteady temperature fields in the stack region and its neighborhood. Once the temperature fields are quantified, heat fluxes and heat transfer coefficients can be determined.

Project 3. In order to overcome an otherwise insurmountable complexity due to the multitude of disparate lengthscales which characterize the thermoacoustic device, we have developed a multi-dimensional non-linear model of an idealized thermoacoustic stack. The model relies on a vorticity-based formulation of the low-Mach-number limit of the mass, momentum and energy conservation equations. The essential features of the approach include the efficiency of the computations, which enables us to isolate and capture the details of complex flow phenomena, and the flexibility of the formulation, which lends itself to various extensions.

Accomplishments

Project 1. In the previous years of this project, we have formulated the approximate model trying to ensure that it reduce to the available exact one in the linear regime. We have been successful in this endeavor and we have carried out numerical simulations of the linear case more precise than those published so far. The extension of the model to the nonlinear domain is however non-unique, and it has been necessary to carry out a substantial study of the nonlinear regime to develop a version with good stability features. The difficulty arises due to the differences between the dispersion relation of the exact and approximate models. While these differences disappear in the linear domain, they do not when, due to non-linearity, different frequencies mix. This causes some modes that should be damped to be instead unstable. We believe to have now solved the problem by adding higher-derivative terms that have a negligible effect in the linear case, but strongly impact the higher frequencies in the non-linear one.

In another part of the work, we have extended the original model to the refrigerator case and we have been able to reproduce several trends observed experimentally. This work is however still in its early stages.

Project 2. In the past, we have successfully designed a model of a thermoacoustic refrigerator that has enabled us to implement the visualization techniques mentioned above. Experiments applying smoke injection to our thermoacoustic refrigerator model are qualitatively in good agreement with numerical studies also conducted under Project 3 of this grant. A substantial effort had to be carried out to make the model suitable for the implementation of the holographic measurement technique. For example, vibrations with amplitudes of less than 1/8 of the laser wavelength of 514.5 nm, can destroy the measurements. These stringent requirements are particularly difficult to meet in a vibrating environment such as a loudspeaker-driven thermoacoustic refrigerator. These problems were successfully solved and holographic images were obtained. Currently digital image processing algorithms are under development. On the basis of the observed interferometric fringe patterns, these will allow us to quantify the temperature fields in the stack region and its neighborhood and to determine heat fluxes and heat transfer coefficients.

As part of our research a systematic approach to the design of thermoacoustic refrigerators was developed based on the short-stack boundary layer approximation. Particularly since nowadays commercial applications of thermoacoustic refrigerators are being developed, it is essential to have fast and simple engineering estimates for the design and optimization of prototypes.

Project 3. In the past, we have restricted application of our low-Mach-number computational model to thermoacoustic stacks operating at low drive ratio, and have exploited this restriction by adopting a simplified form of the energy equation. Despite this limitation, the early version of the model has been useful to study the essential flow features in the neighborhood of the thermoacoustic stack (Worlikar & Knio, *J. Comput. Phys.* (in press); Worlikar, M.S. Thesis, Department of Mechanical Engineering, The Johns Hopkins University, 1995). Recently, the simplified model was used to analyze the response of the stack to the imposed acoustic field, to quantify the stack effective impedance, and to evaluate the validity of various quasi-one-dimensional theories (Worlikar, Knio & Klein, submitted to *J. Acoust. Soc. Am.*, April 1996; Worlikar, Knio & Klein, *J. Acoust. Soc. Am.* **98**, 2961). However, most of our efforts during the past year have focused on generalizing the early model. Specifically, we have been simultaneously working towards two objectives. The first one is to extend the multi-dimensional model by relaxing the assumption of low drive ratio. The second is the development of an efficient low-Mach-number solver which simulates weakly-nonlinear resonance tube acoustics and can be suitably combined with the extended multi-dimensional flow model.

So far, we have designed and tested all of the essential elements needed to proceed towards these objectives. Specifically:

- We have adapted the multiple-scales approach developed by Klein [*J. Comput. Phys.* **121**, 213, 1995] to the simulation weakly-nonlinear acoustic effects within the resonance tube. In collaboration with Prof. Klein, we have tested the performance of this low-Mach-number flow solver and verified that it suitably extends to thermoacoustic applications.

- We have generalized the multi-dimensional model so as to accommodate moderate drive ratios and thermal stratification effects. In doing so, we have tackled two major difficulties. The first concerns the stability of the numerical integration, especially when the medium is strongly stratified. To address these stability concerns, we have resorted to a semi-implicit integration scheme, and have tested its performance under stringent conditions including high-heat-release combustion applications (Knio, Worlikar & Najm, accepted for publication in *Twenty Sixth International Symposium on Combustion*). The second difficulty is due to the stratified divergence field which necessitates the inversion of a Neumann problem. Since the simplified scheme only handled Dirichlet streamfunction boundary conditions, the design of a new, fast elliptic solver proved necessary. We have recently completed the construction of a suitable solver based on a new domain decomposition / boundary Green's function technique.

We are now in the process of assembling these schemes in order to construct two extensions of the previous model: (a) a thermally-stratified stack model, and (b) a thermoacoustic model which couples the low-Mach-number long-wave solver with the local multi-dimensional stack model. Development of these extensions will be the focus of our activities in the coming year.

Publications and presentations

Project 1. Two papers to be submitted to the *Journal of the Acoustical Society of America* are near completion:

1. M. Watanabe, A. Prosperetti, and H. Yuan "A simplified model for linear and nonlinear processes in thermoacoustic prime movers. Part I. Model and linear theory"
2. H. Yuan and A. Prosperetti "A simplified model for linear and nonlinear processes in thermoacoustic prime movers. Part II. Numerical method and comparison with experiment"

The following presentations at Acoustical Society of America meetings have been made:

1. A. Prosperetti and M. Watanabe "Numerical study of a simplified model of nonlinear processes in thermoacoustic engines", Washington meeting, *J. Acoust. Soc. Am.* **97**, 3410.
2. A. Prosperetti and H. Yuan "A simplified model of a thermoacoustic refrigerator", St. Louis meeting, *J. Acoust. Soc. Am.* **98**, 2961.

Project 2. In the past year two papers were published in the proceedings of conferences and one was accepted for publication in the International Journal of Refrigeration. A fourth paper has been accepted for publication in the Proceedings of the National Heat Transfer Conference and a fifth one has been submitted for the Winter Annual Meeting of the American Society of Mechanical Engineers.

1. Herman, C., Wetzel, M., and Leungki Y. S., "Visualization of oscillating temperature and flow fields in a thermoacoustic refrigerator", Proceedings of the Seventh International Symposium on Flow Visualization, Seattle, Washington, pp. 334-340, Begell House, Inc. New York 1995.
2. Herman, C. and Wetzel, M., "Design of a thermoacoustic refrigerator - a case study", AES-Vol.35, ASME, pp. 195-203, 1995.
3. Wetzel, M. and Herman, C., "Design optimization of thermoacoustic refrigerators", accepted for publication in the International Journal of Refrigeration, 1996.
4. Wetzel, M. and Herman, C., "Design issues of a thermoacoustic refrigerator and its heat exchanger", to be published in the Proceedings of the National Heat Transfer Conference in Houston, Texas, August, 1996.
5. Wetzel, M. and Herman, C., "Parameter spaces and design optimization of thermoacoustic refrigerators", submitted for the Winter Annual Meeting of ASME in Atlanta, GA, November, 1996.

The work was presented at five conferences during the past year. At two of these, the Seventh Symposium on Flow visualization and The Winter Annual Meeting of the ASME, the papers mentioned above were presented. Apart from these, three presentations were given at Meetings of the Acoustical Society of America and the abstracts of these presentations were published in the programs.

1. Herman, C., Wetzel, M., and Volejnik, M., "Visualization of oscillating temperature and flow fields in the stack region of a thermoacoustic refrigerator model", presented at the 129th Meeting of the Acoustical Society of America, Washington D.C., June 1995.
2. Herman, C., Wetzel, M., and Wagner, J., "Holographic interferometry: An approach to study the unsteady temperature fields in the stack region and its neighborhood", presented at the 130th Meeting of the Acoustical Society of America, St. Louis, MI, November 1995.
3. Wetzel, M. and Herman, C., "Optimization of the performance of thermoacoustic refrigerators applying the short stack boundary layer approximation", presented at the 131st Meeting of the Acoustical Society of America in Indianapolis IN May, 1996.

Project 3. One paper submitted to *Journal of Computational Physics* in June 1995 was recently accepted. One paper presented at the Second International Workshop on Vortex Flows and Related Numerical Methods, held in Montréal Canada from Aug. 20-24, 1995, has been accepted for publication in the Proceedings. One paper has been accepted for publication in the proceedings of the Twenty-Sixth International Symposium on Combustion;

it will be also presented at the symposium, which will be held in Napoli Italy from Jul. 28 - Aug 2, 1996. One paper has been recently submitted to *Journal of the Acoustical Society of America.*

1. A.S. Worlikar & O.M. Knio, "Numerical Simulation of a Thermoacoustic Refrigerator. Part I: Unsteady Adiabatic Flow around the Stack," *J. Comput. Phys.* (in press).
2. A.S. Worlikar, O.M. Knio & R. Klein, "Numerical Simulation of a Thermoacoustic Refrigerator," accepted for publication in *Proceedings of the Second International Workshop on Vortex Flows and Related Numerical Methods*, (1996).
3. O.M. Knio, A.S. Worlikar & H.N. Najm, "Mixing and Chemical Reaction in an Idealized Swirl Chamber," accepted for publication in *Twenty Sixth International Symposium on Combustion*, The Combustion Institute (1996).
4. A.S. Worlikar, O.M Knio & R. Klein, "Numerical Study of the Effective Impedance of a Thermoacoustic Stack," submitted to *J. Acoust. Soc. Am.*, April 1996.

The following paper has been presented at the 130th Acoustical Society of America Meeting which was held in St. Louis in November 1995.

A.S. Worlikar, O.M. Knio & R. Klein, "Numerical Study of the Effective Impedance of an Idealized Thermoacoustic Stack," *J. Acoust. Soc. Am.* **98**, 2961.

The following M.S. Thesis has been accepted in October 1995.

A.S. Worlikar, *Numerical Study of Unsteady Flow Around a Thermoacoustic Stack*, M.S. Thesis, Department of Mechanical Engineering, The Johns Hopkins University (1995).

Personnel

Project 1. In addition to the P.I. A. Prosperetti, the following students have been involved full- or part-time with this project:

1. MASAO WATANABE: Ph.D. in Mechanical Engineering awarded in January 1995. His collaboration has continued, however, beyond his graduations date. Dr. Watanabe is currently Assistant Professor in the Department of Mechanical Engineering of Kyushu University, Fukuoka, Japan.
2. HE YUAN: Ph.D. Mechanical Engineering expected by September, 1996. Mr. Yuan is completing his thesis while working full-time for INTEC, an electronics company in Connecticut.

3. SERGEY KARPOV: is currently finishing his second year of the Hopkins doctoral program in Mechanical Engineering.

4. JOHN SOKOLOVIC: admitted to the Hopkins doctoral program in Mechanical Engineering in September 1995. He is currently supported by an AASERT fellowship awarded in conjunction with the present thermoacoustic project.

Project 2. In addition to the PI C. Herman, the following students have been involved full time with this project:

1. MARTIN WETZEL: is currently finishing his second year of the Hopkins doctoral program in Mechanical Engineering.

2. JOACHIM WAGNER: completed his Diploma Thesis (comparable to a Master's Thesis) for the Technical University of Munich (Germany) working on this project.

Project 3. In addition to the Co-PI O. Knio, one graduate student, ANIRUDDHA WORLIKAR, has been involved full-time in this project. He has been working on numerical simulation of thermoacoustic devices since the inception of the project. He has completed an M.S. Thesis on the subject in October 1995. His ongoing PhD research effort is an extension of his master's work.

Furthermore, we have also benefited from direct participation of Prof. Rupert Klein, an Associate Professor in the Department of Safety Technology at Bergische Universtität in Germany. Professor Klein was the recipient of the G.W.C. Whiting School of Engineering International Fellow award for 1995-1996. He visited the Department of Mechanical Engineering during Spring of 1996, and dedicated most his visit to work on thermoacoustics at no cost to the present grant. The collaboration with Prof. Klein is ongoing.

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a. Number of papers submitted to refereed journals but not yet published: 4

b. Number of papers published in refereed journals (ATTACH LIST): 0

c. Number of books or chapters submitted but not yet published: 3

d. Number of books or chapters published (ATTACH LIST): 2

e. Number of printed technical reports & non-refereed papers (ATTACH LIST): 0

f. Number of patents filed: 0

g. Number of patents granted (ATTACH LIST): 0

h. Number of invited presentations at workshops or professional society meetings: 0

i. Number of contributed presentations at workshops or professional society meetings: 6

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k. Number of graduate students supported at least 25% this year this contract/grant: 5

l. Number of post docs supported at least 25% this year this contract/grant: 0

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Graduate student FEMALE: 0 Post doc FEMALE: 0

Graduate student MINORITY: 0 Post doc MINORITY: 0

Graduate student ASIAN E/N: 3 Post doc ASIAN E/N: 0

d. Books or chapters published

1. Herman, C., Wetzel, M., and Leungki Y. S., "Visualization of oscillating temperature and flow fields in a thermoacoustic refrigerator", Proceedings of the Seventh International Symposium on Flow Visualization, Seattle, Washington, pp. 334-340, Begell House, Inc. New York 1995.

2. Herman, C. and Wetzel, M., "Design of a thermoacoustic refrigerator - a case study", AES-Vol.35, ASME, pp. 195-203, 1995.