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Close Out Final Report  
June 26, 1989

1) Title - Vortex-Exhaust Nozzle Interactions in Ramjets Combustors

Principal Investigator: J. W. Daily  
Contract Number: N00014-84-K-0372 P00006  
Project Number: 432K-003

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2a) Objectives

The objective of our work was to understand the role of large scale vortical structures in the low-frequency pressure oscillation ramjet problem. We were particularly interested in vortex-nozzle interactions and the relative role of acoustically versus convectively coupled instability mechanisms. *25 \* Exhaust*

2b) Approach

*Nozzles, \* Ramjets, \* Combustors, \* Acoustics*

Our approach was to make observations in a two-dimensional dump combustor operated at conditions similar to those found in operational ramjets. The combustor was designed to allow full optical access and to be able to readily change the important geometrical parameters. The facility was fully instrumented with schlieren visualization, hot film velocimetry, high frequency response pressure transducers, and CH/C2 imaging systems.

The experimental observations were analyzed using the methods of linear stability analysis to predict expected modes of motion, linear acoustical analysis to predict acoustic mode structures, asymptotic expansion of the equations of motion to estimate the expected influence of various modes of motion with respect to the acoustic field, and vortex calculations to numerically simulate the vortex motion. In addition, simple analytic methods were used to model the overall instability mechanism.

3) Summary of Overall Progress

We have performed a series of experiments and analyses that reveal the basic mechanism involved in the low frequency ramjet instability problem to be a coupled acoustic/convective mode, with vortex shedding and dynamics dominating the convective behavior.

The results of our experiments indicate that the basic instability mechanism results from a combination of flow enhanced heat release (extra reactant carried by a vortex) coupled with inlet acoustic timing. The scenario is similar to the "vented explosion" in which early rapid reaction in a closed vessel with small ports dominates the mass conservation and the pressure

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November 13, 1991

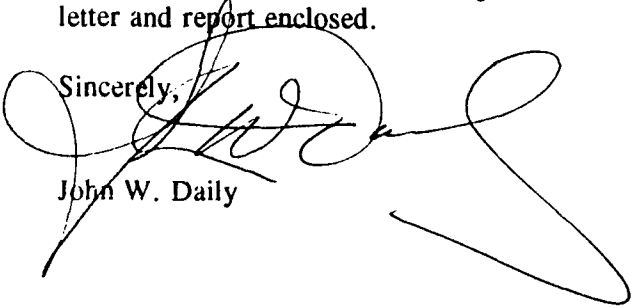
Mr. Linden Clausen  
Administrative Contracting Officer  
Office of Naval Research  
Richmond Field Station  
Richmond, CA 94804-0001

dist.

Dear Mr. Clausen,

In response to your letter dated September 23, 1991 regarding the final technical report for contract N00014-84-K-0372. I sent the report to Dr. Gabriel Roy in June of 1989. Find a copy of the cover letter and report enclosed.

Sincerely,



John W. Daily

COPY

June 26, 1989

Dr. Gabriel Roy  
Scientific Officer  
Propulsion and Energetics Program  
Office of Naval Research  
Arlington, VA 22217-5000

Dear Gabriel,

Find enclosed the report you requested. I am sorry it was late. I misread your letter and thought it was due June 30. I hope it is not too late.

Regards,

John W. Daily  
Professor

rise. When the reaction slows, draining occurs and the pressure drops.

In the ramjet, inlet acoustics force extra reactant into the combustor. Early in the cycle reaction occurs rapidly and the pressure rises. Later in the cycle, drainage out the exhaust and into the inlet dominates and the pressure drops. The schlieren observations reveal that a strong acoustic field results in a pulsating flow. A large mushroom vortex is shed each cycle at the dump plane. It is this vortex which introduces extra reactant into the combustor. When the vortex reaches the nozzle it breaks up and the heat release rate is substantially enhanced and combustion rapidly completed. In addition, the mass flow rate increases as unburned reactant reach the nozzle. The pressure then drops until the inlet acoustics introduce the next vortex.

The period of the oscillation is readily determined as the sum of the acoustic round trip time in the inlet and the vortex convection time in the combustor. The amplitude is more difficult to calculate, being determined by the complex interaction of inlet acoustics and combustor fluid mechanics. However, analysis reveals that to first order, the acoustic and the convective fields are separable except at the flame surface in the combustor and the up and downstream boundaries. Thus analytic modeling of the process to determine amplitude behavior shows promise.

#### 4) Refereed Papers (7)

These were papers related to our work that appeared in print during the grant period. We are presently preparing several papers for journal publication based on the papers we have already presented at meetings.

Keller, J. O., and J. W. Daily, "The Effects of Highly Exothermic Chemical Reaction on a Two-Dimensional Mixing Layer," AIAA Journal, AIAA Journal 23, 1937-1945 (1985).

Daily, J. W., and W. J. Lundquist, "Three-Dimensional Structure in a Turbulent Combusting Mixing Layer," Twentieth International Symposium on Combustion, The Combustion Institute, 485 (1985).

Daily, J. W., R. W. Pitz, J. O. Keller, J. L. Ellzey and I. G. Shepherd, "The Structure and Dynamics of Reacting Two-Stream Plane Mixing Layers," in "Experimental Measurements and Techniques in Turbulent Reactive and Non-reactive Flows," ASME Special Publication AMD-Vol 66, 175 (1984)

Azzazy, M., and J. W. Daily, "The Effect of Reactive Intermediates on the Propagation of Turbulent Premixed Flames," AIAA Journal 23, 1202 (1985).

Shepherd, I. G., and J. W. Daily, "Velocity and Density Measurements in a Planar Two-Stream Turbulent Mixing Layer," AIAA

Statement A per telecon  
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Progress in Aeronautics and Astronautics 105, Part II, 83-98 (1985).

Azzazy, M., J. W. Daily, and M. Namazian, "The Effect of Reactive Intermediates on the Propagation of Turbulent Premixed Flames: Comparison of Experiment and Theory," Combustion and Flame 63, 165-176 (1986).

Daily, J. W., "Cycle-to-Cycle Variations: A Chaotic Process?," Combustion Science and Technology 57, 149-162 (1988).

#### 5) Technical Reports and Non-Refereed Papers (15)

Yu, K., S. Lee, H. E. Stewart, and J. W. Daily, "Vortex-Nozzle Interactions in Ramjet Combustors," JANNAF Combustion Meeting, NASA Langley Research Center (20-24 October, 1986)

Aliabdi, P., D. Dabiri, and J. W. Daily, "Chaotic Analysis of a Plane Mixing Layer," 25th AIAA Aerospace Sciences Meeting, Reno, Nevada, Paper No. 87-0223 (12-15 January 1987).

Trouve, A., K. Yu, and J. W. Daily, "Vortex-Nozzle Interactions in Ramjet Combustors," 23rd AIAA/ASEE/ASME/SAE Joint Propulsion Conference, San Diego, California, 87-1871 (29 June - 2 July, 1987).

Trouve, A., K. Yu, and J. W. Daily, "Low Frequency Pressure Oscillations in a Model Ramjet Combustor," 24th JANNAF Combustion Meeting, Naval Postgraduate School, Monterey, California (5-6 October 1987).

Trouve, A., K. Yu, and J. W. Daily, "Phase Sensitive Schlieren System for Studying Periodic Combustion Phenomena," Western States/The Combustion Institute, Fall Meeting, Honolulu, Hawaii, Paper No. 87-116 (22-25 November 1987).

Trouve, A., S. M. Candel, and J. W. Daily, "Linear Stability of the Inlet Jet in a Ramjet Dump Combustor," AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, Paper No. 88-0149 (11-14 January 1988).

Trouve, A., "One-Dimensional Linear Analysis of Longitudinal Acoustic Modes in a Ducted System," Mechanical Engineering Department, University of California at Berkeley (February 1988).

Bauwens, L. and J. W. Daily, "Acoustically Coupled Combustion Instability in Ramjet Combustors: Scaling Issues," Department of Mechanical Engineering, University of California at Berkeley (May 1988).

Yu, K., A. Trouve, R. Keanini, and J. W. Daily, "Low Frequency Pressure Oscillations in a Model Ramjet Combustor: the Nature of Frequency Selection," 25th JANNAF Combustion Meeting, NASA/Marshall Space Flight Center, Huntsville, Alabama (25-28 October 1988).

Yu, K., A. Trouve, R. Keanini, and J. W. Daily, "Low Frequency Pressure Oscillations in a Model Ramjet Combustor: the Nature of Frequency Selection," AIAA 27th Aerospace Sciences Meeting, Reno, Nevada, Paper No. 89-0623 (9-12 January 1989).

Keanini, R. G., K. Yu, and J. W. Daily, "Evidence of A Strange Attractor in Ramjet Combustion," AIAA 27th Aerospace Sciences Meeting, Reno, Nevada, Paper No. 89-0624 (9-12 January 1989).

Daily, J. W., "Scramjet Combustion Instability: Lessons learned from Ramjet Research," Prepared for the International Aerospace Symposium Nagoya 89, Nagoya, Japan (14-16 February 1989).

Yu, K., A. Trouve, R. Keanini, L. Bauwens, and J. W. Daily, "Low Frequency High Amplitude Pressure Oscillations in a Ramjet Combustor," Prepared for the Joint Meeting of the British and French Sections/Combustion Institute, Rouen, France (18-21 APRIL 1989).

Bauwens, L. and J. W. Daily, "Entropy Wave Instability in Compact Ramjets," Spring Meeting Western States Section/Combustion Institute, Pulman, Washington, Paper 89-29 (1989).

Trouve, A., "Instabilites Hydrodynamiques et Instabilites de Combustion de Flamme Turbulente Premelangees," These de Docteur, Ecole Centrale de Paris (June 1989).

6) Books or Book Chapters - None

7) Patents - None

8) Presentations (28)

"Vortex-Exhaust Nozzle Interactions in a Ramjet Combustor," ONR/NAVAIR Contractors Meeting on Compact Ramjet Combustion Instabilities, Monterey, California (24-25 October 1984)

"The Structure and Dynamics of Reacting Two-Stream Plane Mixing Layers," ASME Winter Annual Meeting, New Orleans, LA (9-14 December 1985)

"Instabilities in Combustors," Gas Research Institute special meeting on Pulse Combustion, Atlanta, GA (27 March 1985)

"The Structure and Dynamics of Reacting Two-Stream Plane Mixing Layers," Seminar, Stanford University, Stanford, California (22 May 1985)

"The Structure and Dynamics of Reacting Two-Stream Plane Mixing Layers," Seminar, Ecole Central, Chatenay-Malabry, France (27 June 1985)

"The Structure and Dynamics of Reacting Two-Stream Plane Mixing Layers," Seminar, University of Rouen, Mount-Saint-Aignan, France (28 June 1985)

"Velocity and Density Measurements in a Free Two-Stream Mixing Layer," 10th International Colloquium on Dynamics of Explosions and Reactive Systems, Berkeley, California (4-9 August 1985)

"Chaos in Combustion," Seminar at University of California, Department of Mechanical Engineering, 6 October 1986.

"Vortex-Nozzle Interactions in Ramjet Combustors," JANNAF Combustion Meeting, NASA Langley Research Center (20-24 October, 1986)

"Chaos in Combustion," Non-linear Dynamics Seminar, Electrical Engineering and Computer Science Department, University of California, Berkeley, CA (1 December 1986)

"Chaotic Analysis of a Plane Mixing Layer," 25th AIAA Aerospace Sciences Meeting, Reno, Nevada (12-15 January 1987)

"Low Frequency Pressure Oscillations in Ramjet Combustors," Comite Mixte/Conference des Grandes Ecoles-U.C. Berkeley, Paris, France (21-22 May 1987)

"Low Frequency Oscillations in a Ramjet Combustor," Seminar at Ecole Centrale, Paris, France (23 May 1987)

"Vortex Nozzle Interactions in Ramjet Combustors," (with A. Trouve and K. Yu) 23rd AIAA/ASEE/ASME/SAE Joint Propulsion Conference, San Diego, California (29 June - 2 July, 1987)

"Low Frequency Pressure Oscillations in a Model Ramjet Combustor," (with K. Yu and A. Trouve) 24th JANNAF Combustion Meeting, Naval Postgraduate School, Monterey, California (5-6 October 1987).

"Low Frequency Pressure Oscillations in a Model Ramjet Combustor," ONR Workshop on Ramjet Combustion Instability and Supersonic Combustion, University of California, Berkeley, CA (17-19 November 1987)

"Phase Sensitive Schlieren System for Studying Periodic Combustion Phenomena," (with A. Trouve and K. Yu) Western States/The Combustion Institute, Fall Meeting, Honolulu, Hawaii, Paper No. 87-116 (22-25 November 1987).

"Linear Stability of the Inlet Jet in a Ramjet Dump Combustor," (with A. Trouve and S. M. Candel) AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, Paper No. 88-0149 (11-14 January 1988).

"Low Frequency Pressure Oscillations in Ramjet Combustors,"

Seminar at the University of Colorado, Department of Mechanical Engineering, Boulder, CO (28 January 1988)

"The Effects of Geometry and Mean Fluid Residence Time on the Frequency of Pressure Oscillation in a Model Ramjet Combustor," (with K. Yu, and A. Trouve) 22nd International Symposium on Combustion, Seattle, WA (14-18 August 1988)

Yu, K., A. Trouve, R. Keanini, and J. W. Daily, "Low Frequency Pressure Oscillations in a Model Ramjet Combustor: the Nature of Frequency Selection," To be presented at the AIAA 27th Aerospace Sciences Meeting, Reno, Nevada (9-12 January 1989)

Keanini, R. G., K. Yu, and J. W. Daily, "A Strange Attractor in Ramjet Combustion," To be presented at the AIAA 27th Aerospace Sciences Meeting, Reno, Nevada (9-12 January 1989)

Daily, J. W., "Scramjet Combustion Instability: Lessons learned from Ramjet Research," Prepared for the International Aerospace Symposium Nagoya 89, Nagoya, Japan (14-16 February 1989).

Yu, K., A. Trouve, R. Keanini, L. Bauwens, and J. W. Daily, "Low Frequency High Amplitude Pressure Oscillations in a Ramjet Combustor," Prepared for the Joint Meeting of the British and French Sections/Combustion Institute, Rouen, France (18-21 APRIL 1989).

Bauwens, L. and J. W. Daily, "Entropy Wave Instability in Compact Ramjets," Spring Meeting Western States Section/Combustion Institute, Pullman, Washington, Paper 89-29 (1989).

Daily, J. W., "Low Frequency Pressure Oscillations in Ramjet Combustors," Seminar at TRW Corporation, Redondo Beach, CA (18 May 1989).

Daily, J. W., "Low Frequency Pressure Oscillations in Ramjet Combustors," Seminar at Societe Europeenne de Propulsion, Vernon, France (14 June 1989).

Daily, J. W., "Low Frequency Pressure Oscillations in Ramjet Combustors," Seminar at Ecole Centrale de Paris, Chatenay Malabry, France (15 June 1989).

#### 9) Honors

Professor Daily received the Ralph R. Teeter Award in 1987. The Award, from the SAE, is for outstanding educators and awarded based on the recipient's contributions to and recognition for teaching.

#### 10) Graduate Students Supported

Janet Ellzey - Research Assistant, Ph.D. September 1985



Stuart Lee - Research Assistant. Received MS degree in December 1987. His MS project was the design of certain components in the test facility, qualifying the facility, and the taking and analysis of hot film cold flow data.

Kenneth Yu - Research Assistant. Received MS degree in December 1987. His MS project was the design of certain components in the test facility, responsibility for the schlieren and LDV setups, and taking and analyzing combustion data. His Ph.D. thesis centers on the experimental observations.

Arnaud Trouve - Research Engineer. Arnaud was a Ph.D. student at Ecole Centrale de Paris, France. His advisor was Professor Sebastien Candel. He spent about a year and a half working for me and I was on his thesis committee. He was responsible for the linear acoustics and linear jet stability analyses and for conducting the experimental investigations with Ken Yu.

Luc Bauwen - Research Assistant. Luc is a Ph.D. student who is only partially supported by this project. He is responsible for the asymptotic analysis and the vortex calculations.

Russell Keanini - Research Assistant. Russ worked for several months with Ken Yu on the experiments. He is the author of a paper on strange attractors seen in the experiments to be presented at the AIAA meeting in January, 1989.

11) Post Docs Supported - None

12) Most Significant Paper

Yu, K., A. Trouve, R. Keanini, and J. W. Daily, "Low Frequency Pressure Oscillations in a Model Ramjet Combustor: the Nature of Frequency Selection," AIAA 27th Aerospace Sciences Meeting, Reno, Nevada, Paper No. 89-0623 (9-12 January 1989).

The most significant paper to date is the one presented at the 1989 AIA Aerospace Sciences Meeting. It outlines the mechanism we have discovered and its physical basis. We are presently preparing a paper for journal publication that incorporates these results plus the results of some additional experiments which support the conclusions reached in this paper.

13) Important Transitions

This is an area of disappointment. The interest showed by the industry does not seem as great as I would have expected. We have transmitted our results to China Lake via Klaus Schadow and Peggy Chan. Only Bob Brown of United Technologies Chemical Systems and Miklos Sajben of McDonnell Douglas Research Laboratories have consistently attended meetings.

With regard to China Lake, we have shown that our results are consistent with cases where the acoustic mode frequencies are much lower than Kelvin-Helmholtz resonances in the dump plane

... mixing layers. Most of Klaus Schadow's data is for cases where the acoustic mode frequencies are higher. Thus we shed large vortices, while his mixing layers are driven to coherence. Both cases appear in practical ramjet designs. The implications for control, however, are somewhat different. In his case, breaking up the coherence can reduce coupling with the acoustic field. In our case it does not necessarily do so, and other means of control will be required.