様式 C-19

科学研究費補助金研究成果報告書

平成２１年　６月　９日現在

研究種目：基盤研究（C）
研究期間：2006　～　2008
課題番号：18560152
研究課題名（和文）　ホールトン自励発振系の平面を射るせん断層による騒音の制御

研究課題名（英文）　Control of the sound generation due to impinging shear layers by the hole-tone feedback cycle

研究代表者
Ｍ・Ａランジェム（M・A Langthjem）
山形大学・大学院理工研究科・准教授
研究者番号：30344815

研究成果の概要：離散渦法及び Powell・Howe 渦音論（theory of vortex sound）を基づいた三次元の数値解析法を開発した。そのほか、数学的に厳密な軸対称のあるモデルも開発した。

交付額

（金額単位：円）

	直接経費	間接経費	合　計
2006 年度	1,600,000	0	1,600,000
2007 年度	1,200,000	360,000	1,560,000
2008 年度	600,000	180,000	780,000
年度			
年度			
総　計	3,400,000	540,000	3,940,000

研究分野：工学
科研費の分科・細目：機械工学・流体工学
キーワード：音響、流力騒音、制御

１．研究開始当初の背景

二次元・軸対称の離散渦法の研究があり、また流力騒音の理論に精通していた。

２．研究の目的

円形空気噴流が同軸上に穴をもつ平板を通過する際に、噴流せん断層で発生した渦が穴のエッジ部に衝突して圧力波が発生する。この圧力波が上流側の噴流出口部に伝播して、せん断層を励起し新しい渦が発生する。そうして音響的なフィードバックループが形成される。

本研究では、空気噴流出口部の内周に設けた圧電アクチュエーターを用いた非軸対称の励起によるホールトンフィードバックサイクルのアクティブ制御コンセプトの実行可能性を研究した。

このために開発した三次元の離散渦法に基づいて自励発振系及びアクティブ制御効果について数値計算によって計算を行った。理論や計算結果を実証するために、実験装置のノズルに設けたアクチュエーター励起システムを構築し、実験を行う。

３．研究の方法

(1) 理論的な解析
- (a) 三次元の離散渦法
- (b) 渦音理論（theory of vortex sound）
- (b) 境界要素法（軸対称のあるモデル及び三次元のモデル）

(2) コンピュータープログラムの開発（Fortran 90）

(3) 数値解析

(4) 計算結果の物理学的な解釈

(5) 実験（予定）

４．研究成果

<u>(1) Axisymmetric formulation</u>

A "mathematically rigorous" acoustic model has been developed for use with a previously developed axisymmetric discrete vortex method. The work is described in detail in Paper 2.

Evaluation of the sound generated by the self-sustained flow oscillations is based on the Powell-Howe theory of vortex sound combined with a thin-plate boundary element theory, to account for the scattering from the end plate. A model for acoustic feedback has been developed. A large number of numerical examples have been prepared. These examples give an understanding of the relative strengths of the contributions from monopole, dipole, and quadrupole source terms. It is found that the contribution from the monopole sources is largest, followed by the dipole contribution. The quadrupole contribution is quite small in comparison. The effect of acoustic feedback (coupling between the incompressible "background" flow field and the acoustic field) has been carefully studied. The acoustic feedback velocity components are too small to alter the fundamental hole-tone dynamics. Still, their effect can be seen on the sound pressure frequency spectra. It is found that they do not alter the peak at the fundamental hole-tone frequency f_0, but reinforce the peaks at the higher harmonics $2f_0$, $3f_0$, ..., and certain combination frequency peaks.

Experimental and computed sound pressure spectra for an observation point placed midway between nozzle exit and end plate, and 1.84 nozzle diameters away from the jest axis, are shown in Fig. 1. It is seen that there is very good agreement between the location of the peaks. The peak levels are however about 6dB too high in the computations (corresponding to a factor 2 in the acoustic pressure).

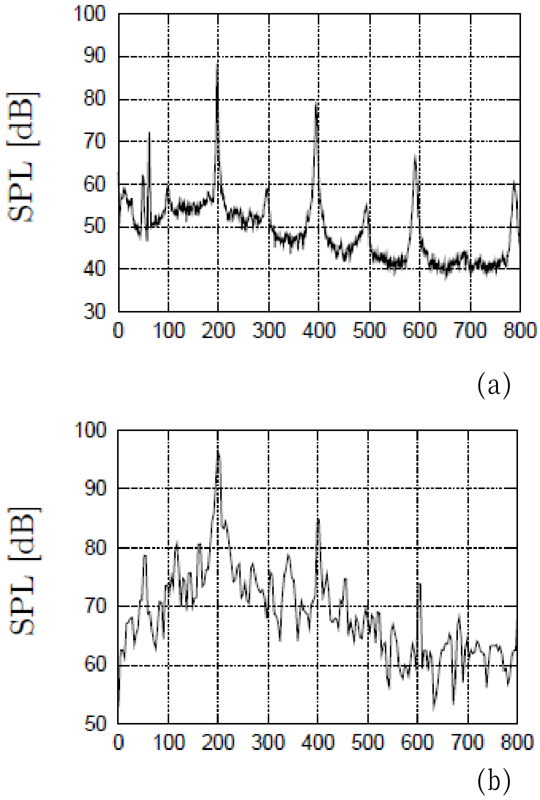

Figure 1. Comparison between (a) experimental and (b) computed sound pressure spectra for the axisymmetric model. [From Paper 2.]

<u>(2) Three-dimensional formulation</u>

A numerical method for simulating the hole-tone problem with the jet subjected to non-axisymmetric "mechanical" ("non-acoustic") perturbations, by piezoelectric actuators mounted at the nozzle exit, has been developed. The work is described in detail in Paper 1.

<u>(2a) Basic flow</u>

The computation of the noise-generating "background flow" is based on a three- dimensional discrete vortex model. The deformable vortex rings are made up of a number of vortex filaments, where the nodes are interpolated via cubic splines. The solid surfaces are represented by quadrilateral vortex panels. The mean jet flow is provided by a number of vortex panels placed on the `back' of the nozzle tube. As in the axisymmetric formulation, the sound generation is evaluated using the Powell- Howe theory of vortex sound. The scattering by the end plate is taken accurately into account by employing a special thin-surface boundary element method.

During initial numerical trials runs it was found that vortex rings tended to "jam up" in front of the end plate, circulating around a small path there, disturbing the rings that are released later. In reality such "standing" vortices will be diffused away due to viscous dissipation. To simulate this effect in a simple way the strength of every vortex ring is reduced according to the decay law for the Lamb-Oseen vortex. This has cured the problem of excessive numerical noise, and a very clean acoustic pressure signal is obtained.

Figure 2 shows a comparison between experimental and computed sound pressure spectra, again for an observation point placed midway between nozzle exit and end plate, and 1.84 nozzle diameters away from the jet axis, as in Fig. 1.

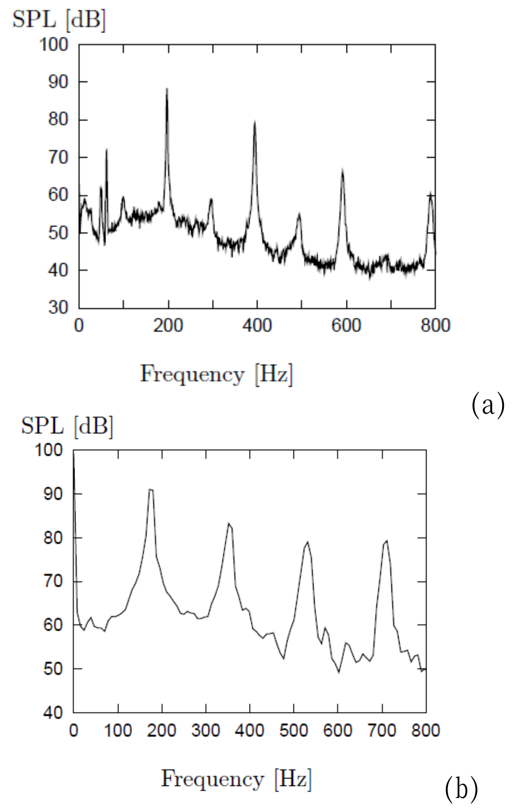

Figure 2. Comparison between (a) experimental and (b) computed sound pressure spectra for the three-dimensional model. [From Paper 1.]

Here there is a very good agreement between the peak levels. The theoretical value of the fundamental component f_0 is however approximately 175 Hz while the experimental value is 196 Hz. Clearly, the discrepancy is amplified in the higher harmonics $2f_0$, $3f_0$. Without the Lamb- Oseen dissipation mechanism the theoretical frequency is about 190 Hz, but the flow (and the acoustic pressure signal) is, again, polluted wit excessive numerical noise. It is believed that f_0 can be moved up 10-20 Hz by a proper choice of initial vortex ring thickness and vortex strength decay model (via numerical experimentation). But we have not carried it out at this point, and have chosen to submit the results shown here for international publication (Ref. [1]).

<u>(2b) The effect of non-axisymmetric flow perturbations</u>

The piezoelectric actuator system is simulated by periodical "edge wave" deformations of the nozzle end section, as illustrated in Fig. 3.

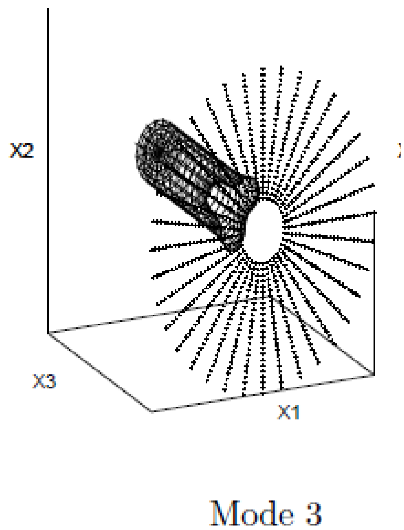

Figure 3. Illustration of the perturbation mechanism at the nozzle end. [From Paper 1.]

Both "shell vibration type" perturbations and rotating perturbations have been considered. The effect of a shell-type perturbation in mode 3 (as shown in Fig. 3) on the acoustic pressure spectrum is illustrated by Fig. 5. Comparing this with Fig. 2(b) it is seen that the peak amplitude at f_0 has been decreased by approximately 6 dB, corresponding to a halving of the acoustic pressure amplitude. Also, the higher harmonics are basically eliminated.

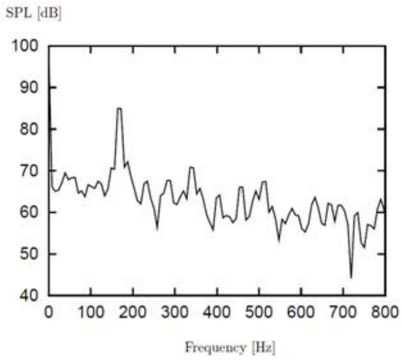

Figure 4. Computed sound pressure spectrum for the case with shell-vibration-type perturbations in mode 3, applied at the nozzle exit. The excitation frequency is 66.67 Hz, while the excitation amplitude is 1/30 of the nozzle diameter.
[From Paper 1.]

A rotating perturbation turns out to be much more efficient in reducing the sound. In fact, the computations indicate that the hole-tone generation may be eliminated all together in this way. Figure 4(a) shows a "snapshot" of the flow with undisturbed nozzle. Here the shear layer rolls up into big, coherent "vortex rings". Figure 4(b) shows a similar "snapshop" for the case with a rotating perturbation. A smoke ring roll-up is not initiated; instead the shear layer is, apparently, able to "creep silently" through the hole in the end plate. The sound pressure spectrum is shown in Fig. 5. When comparing wit Fig. 2 it is seen that the sound generation is virtually eliminated.

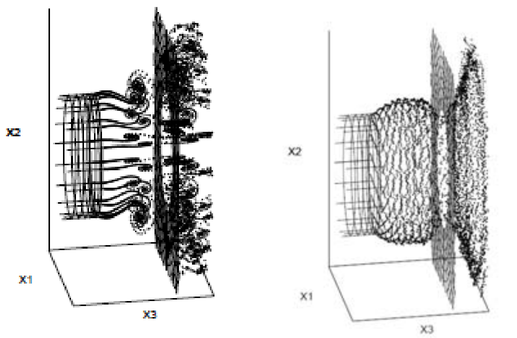

Figure 5. Left: Appearance of the jet with unperturbed nozzle. Right: With a rotating nozzle perturbation (mode 3).
[From Paper 1.]

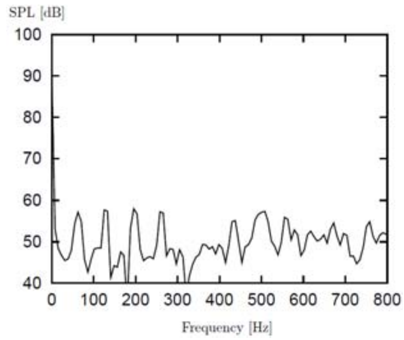

Figure 6. Computed sound pressure spectrum for the case with a rotating perturbations in mode 3, applied at the nozzle exit. The excitation frequency is 66.67 Hz, while the excitation amplitude is 1/300 of the nozzle diameter. [From Paper 1.]

(3) POD analysis

A computer program for determining the fundamental, orthogonal modes of the oscillating flow has been developed, based on Proper Orthononal Decomposition (POD). It is the hope that this could contribute to a better understanding of the mode jump phenomenon, where the fundamental frequency f_0 suddenly shifts. It must be admitted that more work is needed here. But the necessary numerical tool is now at hand.

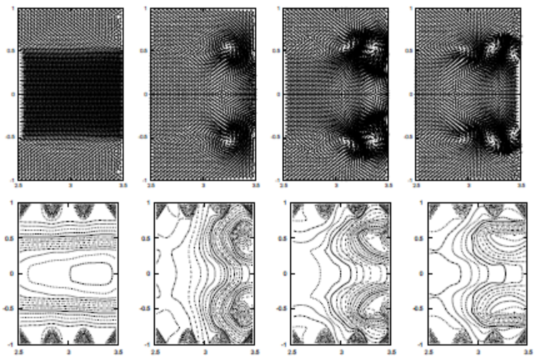

Fig. 7. POD modes 1 through 4 (from left to right). Upper row: Velocity vector plots (with nozzle exit on the left edge and the hole in the end plate on the right edge in each sub-figure). Lower row: Iso-velocity contour plots.
[From Paper 8.]

(4) Experiments

Modification work on an existing experimental setup has been - and is still-going on. A number of piezoelectric actuators have been purchased and response tests have been carried out. Experiments have been made on a system with a limited number of actuators working on the outer side of a thin aluminum-cylinder (to get a smooth inner side for the flow.) Some problems are however remaining, e.g. with resonance of the cylinder.

In summary, more work is necessary on the experimental setup. Experimental verifications of the numerical results are essential, and the experiments *will* be carried out. But we need to report that we have not been able to complete the necessary modifications within the time limit of the present project.

５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計 11 件）

1. M. A. Langthjem, M. Nakano, A three-dimensional numerical study of the hole-tone feedback problem. Journal of Computational Physics 2009 (submitted)
   査読：有

2. M. A. Langthjem, M. Nakano, Numerical study of the hole-tone feedback cycle based on an axisymmetric formulation. Fluid Dynamics Research, 2009 (accepted for publication, in press)
   査読：有

3. M.A. Langthjem, M. Nakano, A three-dimensional study into non-axisymmetric perturbations of the hole-tone feedback cycle. In: Proceedings of the IUTAM Symposium "Unsteady Separated Flows and their Control", Corfu, Greece, 18-22 June 2007 (M. Braza, K. Hourigan, eds.) 5 pp, Springer-Verlag, 2009 (ISBN: 978-1-4020-9897-0)
   査読：有

4. M.A. Langthjem, M. Nakano, Sound generation in the hole-tone feedback problem, RIMS 研究集会, 非線形波動現象の数理と応用, RIMS 講研録 1645, 2009, pp. 221-230.
   査読：無

5. M.A. Langthjem, M. Nakano, The effect of non-axisymmetric flow disturbances on the sound generation in the hole-tone feedback cycle. In: XXII International Congress of Theoretical and Applied Mechanics (ICTAM 2008) (CD-ROM), 2008, 2pp. (Paper# 10414)
   査読：有

6. M.A. Langthjem, M. Nakano, ホールトーンフィードバック問題での自励流体振動の制御[Control of self-sustained flow oscillations in the hole-tone feedback problem] In : 第 51 回自動制御連合講演会、論文集 (CD-ROM), 2008, 5 pp.
   査読：無

7. M.A. Langthjem, M. Nakano, Numerical study of the hole-tone feedback cycle. In: 日本応用数理学会 2008 年度年会講演予稿集, 2008, pp. 101-102.
   査読：無

8. M.A. Langthjem, M. Nakano, Self-sustained flow-oscillations in the hole-tone problem. In: 非線形波動現象の数理と応用. 数理解析研究所講究録 1594, 2008, pp. 18-33.
   査読：無

9. M.A. Langthjem, M. Nakano, Control of sound generation in the hole-tone feedback cycle by non-axi-symmetric flow perturbations. In: 日本流体力学会　年会 2007 講演要旨集 (CD-ROM), 2007, 2 pp.
   査読：無

10. M.A. Langthjem, M. Nakano, A numerical study on the influence of non-axi-symmetric flow perturbations in the hole-tone feedback problem. In: 非線形波動現象の数理と応用. 数理解析研究所講究録 1543, 2007, pp. 21-30.
    査読：無

11. M.A. Langthjem, M. Nakano, Influence of non-axisymmetric perturbations on the hole-tone feedback cycle: A numerical study. In: Proceedings of Inter・Noise 2006, Honolulu, HI, USA (CD-Rom), 2006, 9 pp. (Paper # 279)
    査読：無

〔学会発表〕（計 10 件）

1. M.A. Langthjem, M. Nakano, Aspects of the hole-tone feedback problem. 第 28 回流力シンポジウム, 2008 年 12 月 6 日, 東京大学工学部本郷キャンパス

2. M.A. Langthjem, M. Nakano, ホールトンフィードバック問題での自励流体振動の制御[Control of self-sustained flow oscillations in the hole-tone feedback problem] 第 51 回自動制御連合講演会, 2008 年 11 月 22 日, 山形大学工学部, 米沢キャンパス

3. M.A. Langthjem, M. Nakano, Aspects of the hole-tone feedback problem, RIMS 研究集会, 非線形波動現象の数理と応用, 2008 年 10 月 23 日, 京都大学数理研究所

4. M.A. Langthjem, M. Nakano, Numerical study of the hole-tone feedback cycle. 日本応用数理学会 2008 年度年会, 2008 年 9 月 17 日, 東京大学柏キャンパス

5. M.A. Langthjem, M. Nakano, The effect of non-axisymmetric flow disturbances on the sound generation in the hole-tone feedback cycle. XXII International Congress of Theoretical and Applied Mechanics (ICTAM 2008), 2008 年 8 月 25 日

6. M.A. Langthjem, M. Nakano, POD-based analysis of self-sustained flow-oscillations in the hole-tone problem. RIMS研究集会, 非線形波動現象の数理と応用, 2007年9月18日, 京都大学数理研究所

7. M.A. Langthjem, M. Nakano, Control of sound generation in the hole-tone feedback cycle by non-axi-symmetric flow perturbations. 日本流体力学会年会 2007 年度, 2007 年 8 月 7 日, 東京大学教養学部

8. M.A. Langthjem, M. Nakano, A numerical study on the influence of non-axi-symmetric flow perturbations in the hole-tone feedback problem. RIMS 研究集会, 非線形波動現象の数理と応用, 2007 年 10 月 30 日, 京都大学数理研究所

9. M.A. Langthjem, M. Nakano, A three-dimensional study into non-axisymmetric perturbations of the hole-tone feedback cycle. IUTAM Symposium “Unsteady Separated Flows and their Control". 2007 年 6 月 20 日, Corfu, Greece

10. M.A. Langthjem, M. Nakano, Influence of non-axisymmetric perturbations on the hole-tone feedback cycle: A numerical study. Inter・Noise 2006, 2006 年 12 月 6 日, Honolulu, HI, USA

〔図書〕（計 0 件）

〔産業財産権〕
○出願状況（計 0 件）

○取得状況（計 0 件）

〔その他〕

6．研究組織
(1)研究代表者
M・Aランジェム（M・A LANGTHJEM）
山形大学・大学院理工研究科・准教授
研究者番号：30344815

(2)研究分担者

(3)連携研究者

(4)研究協力者
中野　政身（NAKANO Masami）
東北大学　流体科学研究所