1-66

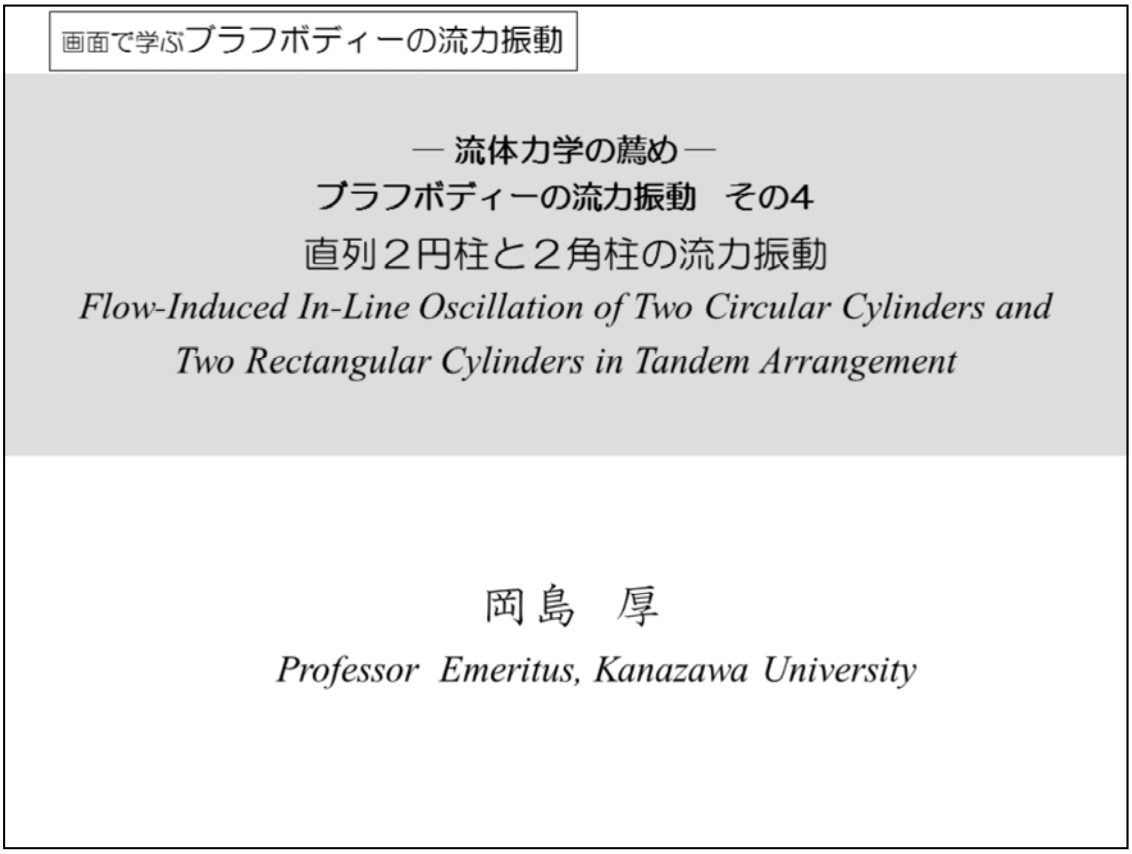
画面で学ぶ
ブラフボディーの流力振動

１．円柱の流力振動
Flow-Induced Oscillations of Circular Cylinders

２．矩形柱の流力振動
Flow-Induced Oscillation of Rectangular Cylinders

３．振動流における物体の流体力学
Fluid Dynamics around a Bluff Body Submerged in Oscillatory Flow

４．直列２円柱および２角柱の流力振動
Flow-Induced Oscillation of Two Circular Cylinders and Two Rectangular Cylinders in Tandem Arrangement



1．矩形柱の静特性： Fluid-dynamic characteristics of rectangular cylinders

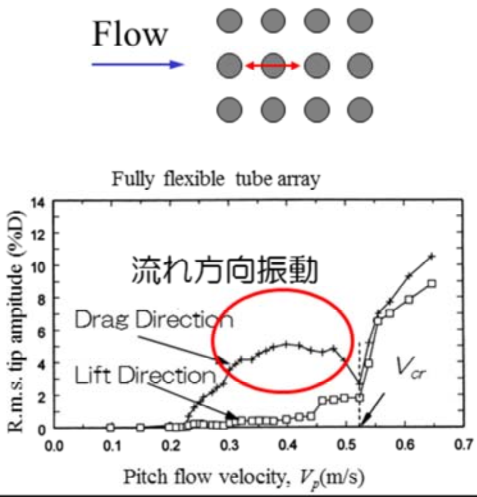
後流に渦が形成されるブラフ・ボディーのうち、種々な断面比の矩形柱の静特性、特にレイノルズ数変化と断面比に対する抗力係数、後流の渦ストローハル数の変化、そして矩形柱周りの流れパターンの変容について、実験結果やLESシミュレーションの結果を用いて説明する。

2．矩形柱の流力振動：Flow-Induced Oscillation of rectangular cylinders

種々な断面比の矩形柱では、流れ方向振動、直角方向振動の渦励振やギャロッピングなどの自励振動(フラッター)が生じる。種々な矩形断面柱の流力振動現象を、実験結果やLESシミュレーション結果を用いて説明する。

各種プラントの配管内構造物などに利用されるブラフボディには,流力振動(Flow-Induced Vibration)が発生する.

熱交換器など複数構造物が近接すると,単独物体と比べ流れ特性はより複雑になり,新たな流力振動が起こる.



直列に配置した2円柱の後方にスプリッタプレートを設置し,流れ方向振動について研究した.

風洞を用いて,一様流中に直列に配置した2円柱の後方にスプリッタプレートを設置し,下流側円柱を自由振動させ,振動模型の流れ方向振動特性と,流れの可視化から後流渦パターンとの関連を模型間隔を変えて,実験を行った.

◎複数物体周りの流れ現象の面白さ:

◎複数物体の静特性:

近年, 熱交換器, 送電線鉄塔, 多脚煙突, 橋梁, 円筒状建築物および海洋構造物など, 一様流中にある複数円筒状構造物の空力特性および空力弾性的不安定振動などが注目されている. 本研究では, その最も基本的な場合として, 流れに直列におかれた2本円柱の場合を取扱う. 直列2本円柱まわりの流れ庭関する研究は, 古く1933年Biermannら(1)による抵抗の測定以来, 今日まで直列2本円柱の空力弾性的不安定性に関する研究なども含め,数多く成されている(2)－(12). しかし, それらの実験の円柱直径に関するレイノルズ数は比較的低く, 上流側円柱まわりの流れは亜臨界域である. しかし, 実際にしばしば起こり得る, 更に高いレイノルズ数範囲の直列2本円柱に関する実験的研究はほとんどない. 一方, 一様流中における単独円柱の場合でも, 一般に臨界レイノルズ数以上の高いレイノルズ数範囲の風洞実験は難しい. そこで文献(13)では単独円柱表面に表面粗さを付けることにより. 円柱表面の境界層の層流から乱流への遷移を促進させ, 臨界レイノルズ数を低下させることを試みた.その結果,比較的低いレイノルズ数で円柱まわりの流れは超臨界域となり円柱表面に層流気ほうが形成される. その時の抵抗は極端に減少し,後流幅は狭くなり,後流の速度変動の卓越するストローハル数は亜臨界域に比べ大きくなる. そして更に層流気ほうが消滅し, 円柱表面境界層が直接乱流はく離するような極超臨界域(post-critical region)の流れが風胴実験で実現することができ, その時の円柱後流に極めて周期性の高いうず列が形成されることなどを明らかにした. すなわち

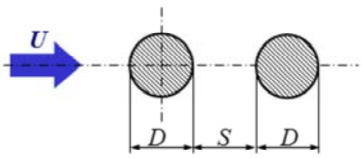
，高レイノルズ数における単独円柱まわりの流れおよび後流の様相は，臨界レイノルズ数以上でかなり変化する．従って，本研究の直列2本円柱の場合，上流側円柱まわりの流れが超臨界域や極超臨界域の時には，流れの様相は更に複雑になると考えられる．そこで本研究では，上流側円柱まわりの流れが超臨界域および極超臨界域であるような高いレイノルズ数において，直列2本円柱の抵抗や後流の速度変動の周波数などを測定し，その静的空力特性を明らかにするとともに，油膜法により円柱表面近傍の流れを可視観察し，流体力と流れの関連性を考察する．なお，文献(13)では単独円柱の場合の数種類の表面粗さにつき，その効果を調べたが，本実験ではそのうち最も代表的な2種類の表面粗さを用いた。

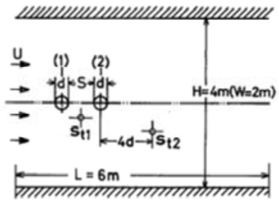
◎複数物体の流力特性：

Two Tandem Cylinders in a Flow

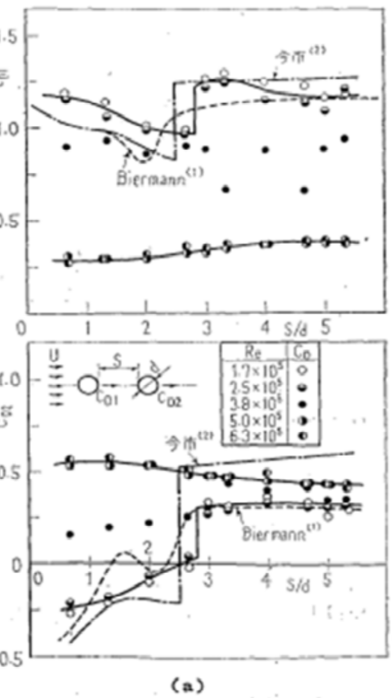
(1) Statistic Characteristics of High Reynolds Numbers

(2) Aeroelastic Characteristics

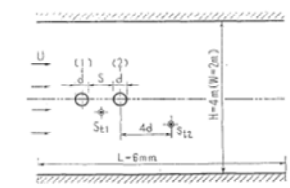




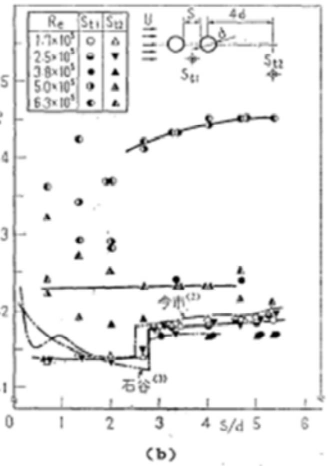
直列2本円柱



隙間S/dに対する滑面直列2本円柱の抵抗C_{D1},C_{D2}



滑面直列2本円柱の配置概略

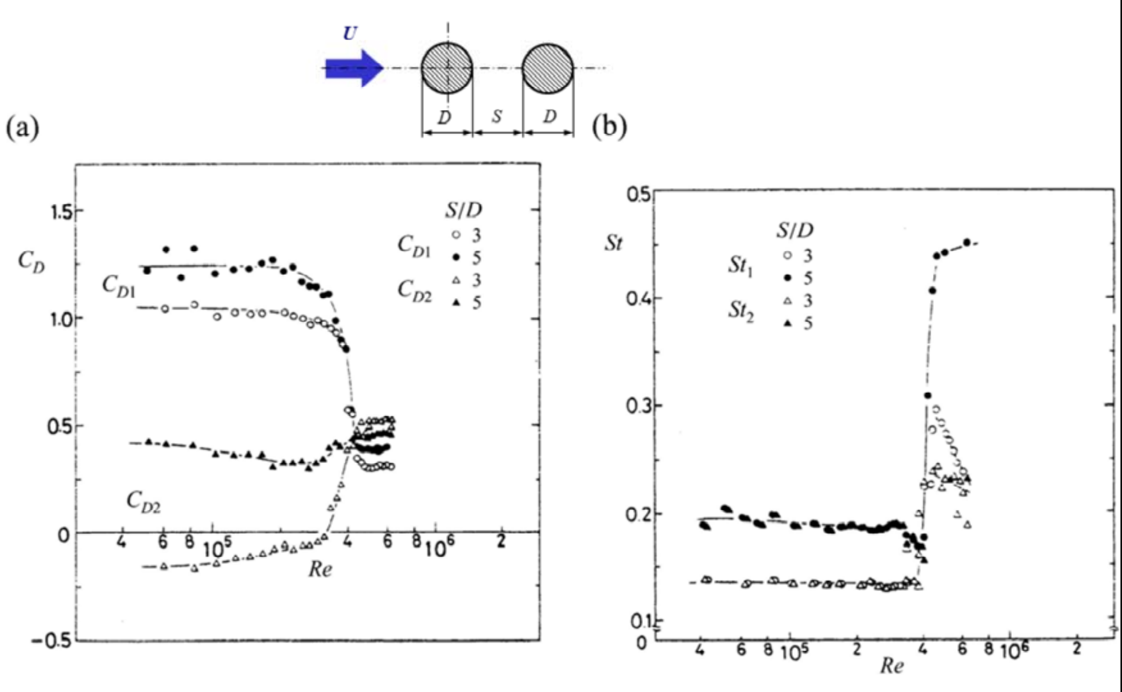


隙間S/dに対する滑面直列2本円柱の抵抗St_1,St_2

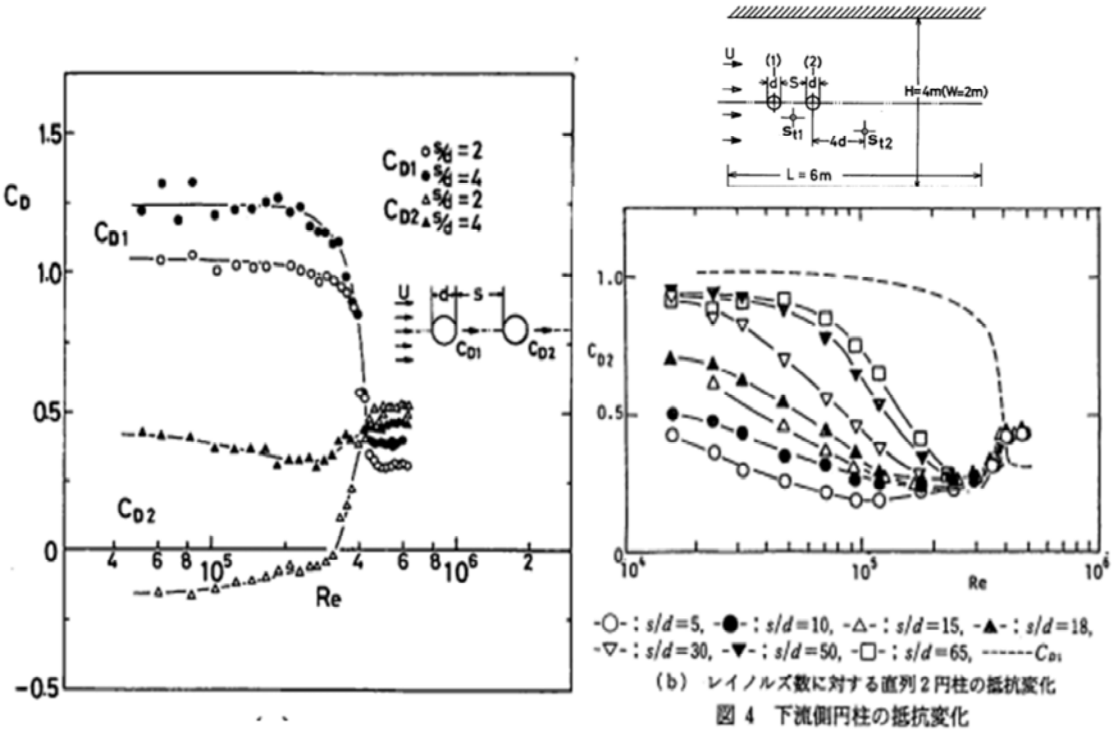
３．１．2間隔S/dの影響：

次にRe=1.7×10^5, 2.5×10^5(亜臨界), 3.8x10^5(臨界域), 5.Ox10^5,6.3×10^5(超臨界域)の場合を例にして，間隔S/d=0.7～5.3の範囲の(C_{D1}, C_{D2})と(St_1,St_2)の変化を図5(a),(b)に示す．図にはBiermannら(1)(Re=10^5)，今市ら(2)(Re=2.1x10^4)，石谷ら(8)(Re=1.5x10^3～10^4)の値とも比較してある．これらの実験はいずれも亜臨界域のもので．本実験のRe=1.7X10^5, 2.5×10^5の値とよい一致がふられる．特にC_{D2}の本測定値はRe数の最も近いBiermannらの値に一致している。またC_DやSt数の値が間隔S/dに対し，ステップ状に変化するS/dの値は、この場合2.8である．亜臨界域におけるC_DやSt数値のステップ状に変化する現象は，上流側円柱背後のうず形成領域と下流側円柱の位極との相対的関係に密接に関連しており，これらに関して石谷ら(8)によるシュリーレンソ写真による可視観察やうずの周波数測定，今市ら(2)による圧力の詳細な測定および渡辺ら(6)による流体力の測定などがある．これらの結果や本実験結果から亜臨界域で間隔の狭い場合，両円柱間の速度変動はわずかで，上流側円柱背圧と下流側円柱のよどみ点圧力はほぼ等しく，下流側円柱背後のみうず列が生じ，2本円柱流れはむしろ死水域で継がれた一つの物体まわりの流れの挙動を呈するといえる．そしてS/d=2.8を境にして流れは変化する．すなわち，2本円柱間でも流れの周期的変動が強く感知されるようにたり，C_DやSt数の値が急変する．図5(b)に示すように，亜臨界域のS/d＞2.8の上・下流側円柱背後のSt数は，共にSt_1=St_2=0.19で単独円柱の場合に等しい。 またC_Dは、図5(a)から，C_{D1}=1.2で単独円柱の値に近く，C_{D2}=0.3でかなり小さい．次に，臨界域(Re=3.8x10^5)の場合，C_DやSt数の値はS/d=0.7～5.3にわたり，亜臨界域と次に述べる超臨界域における値の中間的傾向を示し，S/dの影響はわずかで，特にSt数の値のばらつきが目立つ。そして，上流側円柱に層流気ほうの形成されている超臨界域

(Re=5.0×10^5, 6.3×10^5)の場合,図5（a), (b）に示すように，両円柱の（C_{D1}, C_{D2}）と（St_1,S t_2）の値に及ぼすS/dの影響は少なく，わずかにS/dの増加に伴い，C_{D1}は漸増するのに対し，C_{D2}は漸減し，両者の値が接近しているが，本実験範囲では，C_{D1}よりC_{D2}のほうが常に大きな値である．この場合，上流側円柱における層流気ほうの形成によりC_{D1}の値は亜臨界域に比べ減少する．同時に上流側円柱背後の逆流領域が極端に縮小し，後流幅が狭くなることにより，CD図は逆に増大する．しかも図3（b）に示したごとく，下流側円柱の流れには層流気ほうは無く，約θ=120゜。付近で乱流はく離している．図6には油膜法によって求めた超臨界域（Re=5.Ox10^5）における流れのはく離点や，再付着点の位歴のS/‘に対する変化を示す．図から上流側円柱の層流気ほうの位歴や上・下流側円柱のはく離点の位図などはS/d=0.07～4.67の範囲であまり変わらない．このことは，図5（a）の超臨界域においてC_{D1}やC_{D2}の値がS/dに対し，大きな変化がないことに対応している．



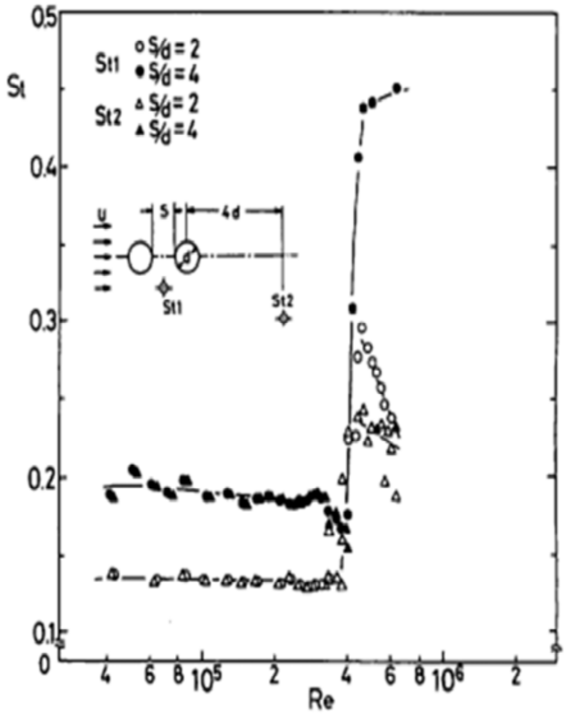
ɪɢ. 26.19. Tandem cylinder for $S/D = 3$ and 5, (a) drag, (b) Strouhal numb
Okajima (1979J)



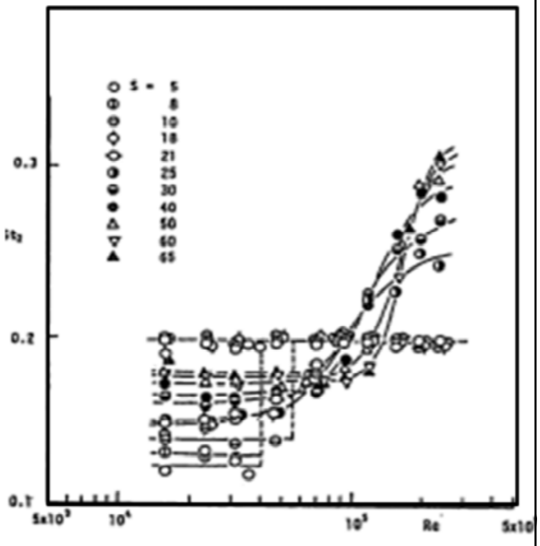
Re数に対する滑面直列2本円柱の
抵抗C_{D1},C_{D2}

上・下流側円柱に作用する抵抗係数CD1,(2)=、1,(2)／
1/2joU2`J(Dは抵抗,10は空気密度，添字1は上流側，
2は下流側を示す)，および上・下流側円柱背後のス
トローハル数（s`数）S",(2)=ガル(2)/U(ハ,(2)は速度
÷変動の周波数)，そして2本円柱まわりの流れにつき，
レイノルズ数（R・数）や2本円柱の間隔S/αを変
え，それらの影響を議論する.
３．１滑面円柱の場合
3.1.1R`数の影響円柱間隔S/d=2，4の場合
を例にして，R-0.53×105～6.3×10sの範囲の直列
2本滑面円柱に働く抵抗(CDI,cD2)およびSl数(S虹,
S`函）の変化を図2（a),（b）に示す．図によれば，上
流側円柱のCDI,Smの値はR・数が約3×10sに達するまで大きな変化はなく，
CD,=1.0(S/ゴー2)，1.2(S／
d=4),S`,=0.14(S/`=2，速度変動の振幅は非常に小
さい)，0.19(S/`=4）である．そして臨界R`数の
Rc・デー3.8×10s付近でcDLShの値は急激に変化し，
R､＞4.4×10sの範囲ではCD!=03(S/`=2)，0.4(S／
α=4）でかなり小さい値となる．一方この時の卓越す

るS`数の値は大きくなる．結局，S/Cf=2，4の場合
共に，上流側円柱の抵抗やS`数のR`数に対する変
化は単独円柱の場合('8)とほぼ同様の様相を呈し，そ
の臨界R`数の値もR…=3.8×10sで単独円柱と変
わらない．
一方，下流側円柱のCD2,s`2の値は主として上述の
ような上流側円柱まわりの流れの変化に付随して変わ
る．すなわち，尺。＜3.Ox105のR・数範囲ではCD2は
推力CD=-0.1～0（S/α=2）あるいは比較的小さい
値cD2=0.4～0.3(S/α=4）で，S`動の値は上流側の
Snと同じである．そしてCDI,S`，の値が急変する臨

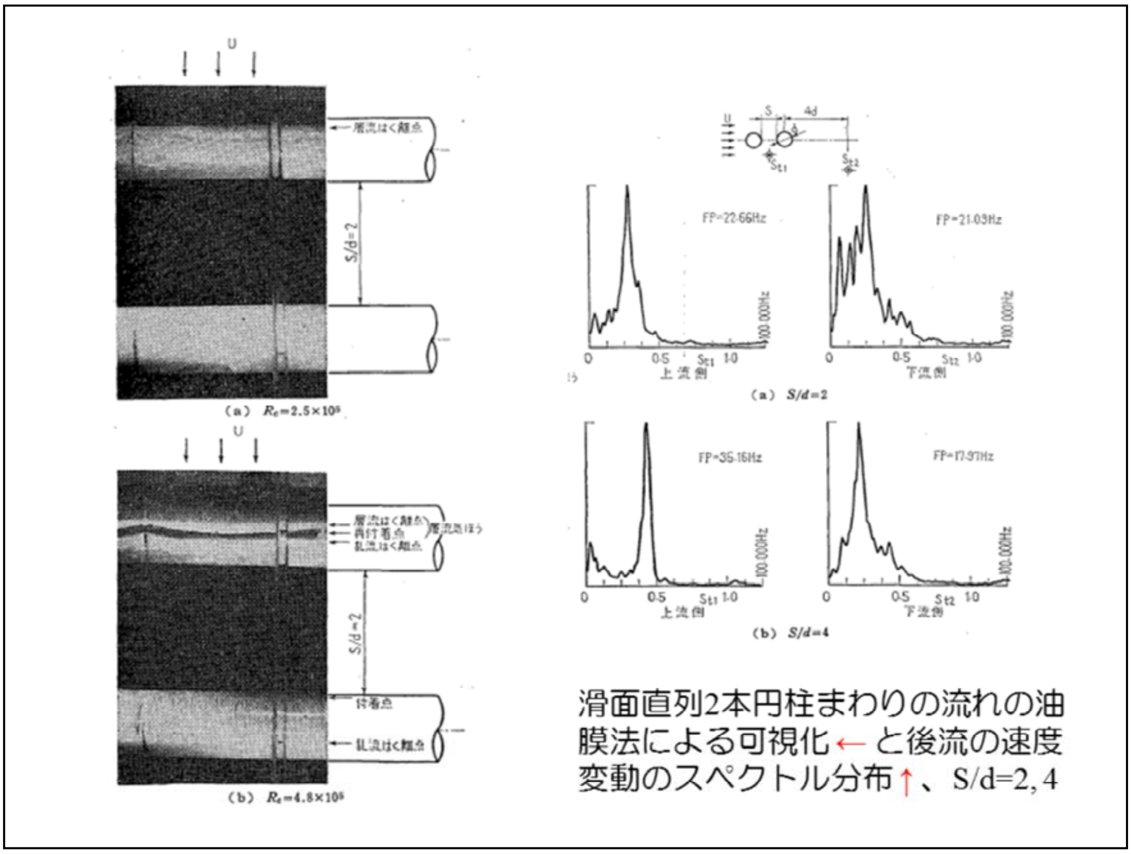


Re数に対する滑面直列2本円柱の抵抗St_1,St_2



（b） レイノルズ数に対する下流側円柱後流のストローハル
化

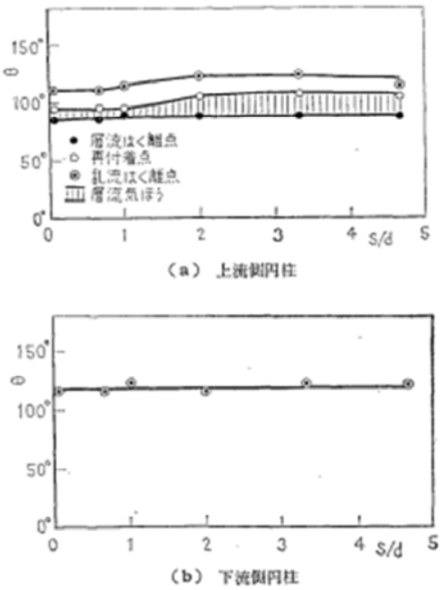
図 8 下流側円柱後流のストローハル数変化



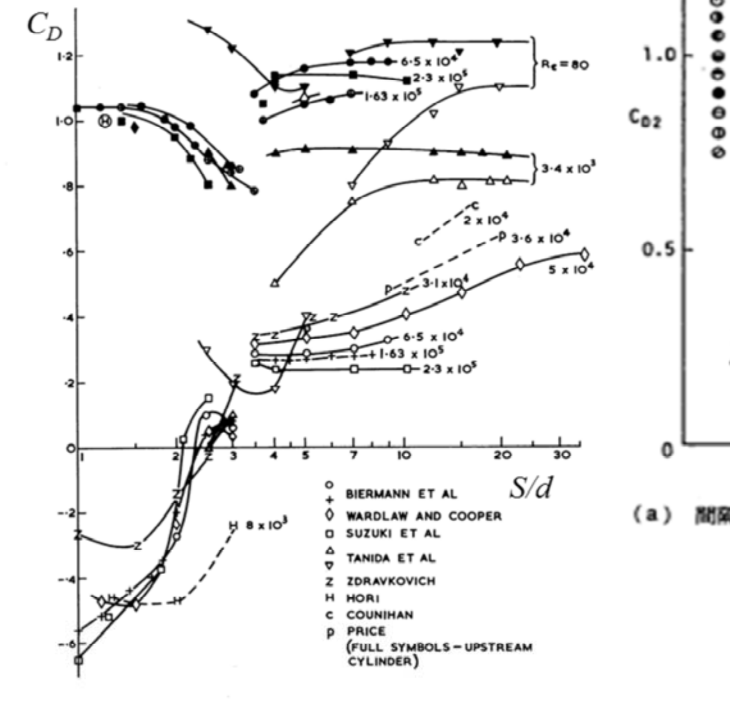
界R僅数付近でCD2，s:量の値も同時に変化し，R`＞,好lx1O，では，111]開S/dにほとんど依存せず，cD2=0.5で，上流側円住のcD1よりむしろ大きな値である．

次に，円柱近挽流れの抽暎法による可視観察結果を図3(a),(b)に示す．図3(a)(R－25x10s，S/d=2)の上流側円柱においては，白色の油膜が吹含取られ，黒色の円柱表面が露出している部分と抽瑛の残っている部分に減別され，その塊界はよどみ点から約0=70.の位肚で，この付近から塊界層は圃流はく離している．上流側円柱まわりの流れは亜臨界域である．下流側円柱の油膜模様は判然としない．一方，図3(b)(R暦－1．8×103,S/`=2)の場合，上流側円柱の油暎模樺は四つの部分に分かれている.よど象点からβ=90°までの汕談の箒い部分，0=90。～105°の白い抽膜の残っている部分，β=105。～120゜の油膜の全く無い部分，そして'＞120゜の抽膜の残っている部分である．しかも，この油膜換槻はスパン方向にほぼ直線で，流れは二次元的である.この場合，流れは

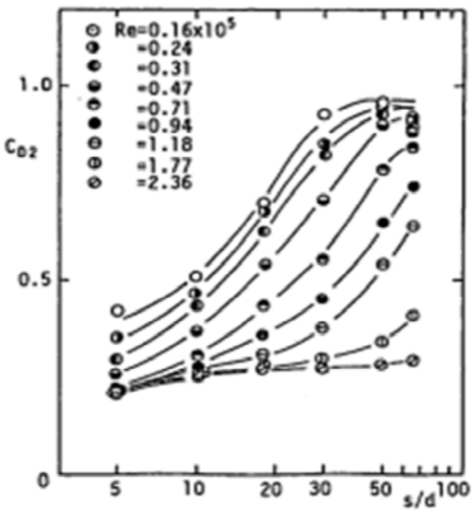
,=90° で屑流ばく雄するが，β=105° で再付着して，
層流気ほうを形成し，β=120° で乱流はく離している．流れは超臨界域である．下流側円柱の流れは0=30。付近から円柱に沿い，0=125.で乱流ばく離していることが観察される．図4（a）にはこの時の円柱後流のパワースペクトル密度分布を示すが，上．下流側のS`数，S…S`1の帯域はかなり広く，その卓越するS』数はそれぞれ梱逸している．さらに，図4(b）にはS/‘－1の掛合を示すが，上流0Mの卓越するS‘政は,Sk3=0．45で11i独円柱の超臨界域の場合に一致している．そしてこの周波数成分は比較的早く減衰し，下流側円柱ではその成分はわずかに検出される極度で，下流側の」;f趣Sl数はS`，と異なり，S:。=0.23である．以上の結果から直列2本円柱まわりの流れのR・数に対する変化は，主として上流側円柱流れの変化に支配されていると言える．すなわち臨界R`数以上では，単独円柱同様上流側円柱に層流気ほうが形成され，乱流はく離点は後退し，上流側円柱背後の逆流領域の大きさが縮小し,しかも後流幅も狭くなる.このような流れの変化に対応して下流側円柱まわりの流れは変化する．従って図2（a),（b）に示すごとく，直列2本円柱の（CDhCD2）や（S“S`2)の値は上流側円柱の臨界R・数a8x105付近で同時に変化している．そこで以後，直列2本円柱の上流側円柱まわりの流れが亜臨界域，臨界域，超臨界域，極超臨界域であることを，便宜上単に亜臨界域，臨界域，超臨界域，極超臨界域と呼ぶことにする．



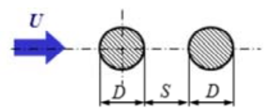
滑面直列2本円柱の剥離点および再付着点の位置、$Re=5.0\times10^5$



26.18. Compilation of drag coefficients on tandem cylinders in terms of S/D and Re, Zdravkovich (1977R)



（a） 間隔 s/d に対する下流側円柱の抵抗変化



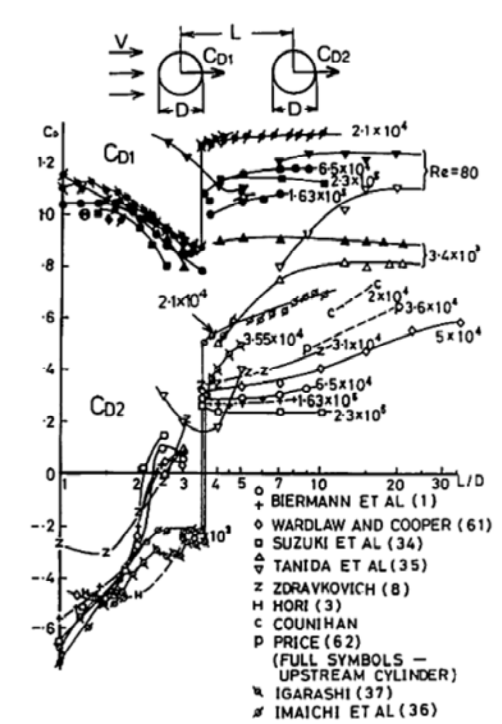
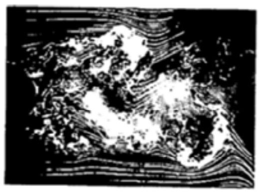
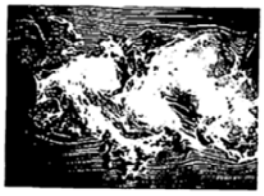


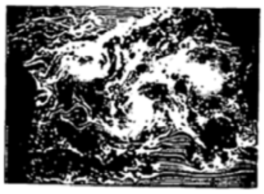
Figure 29. Drag coefficients of two tandem circular cylinders [7, 35–37].



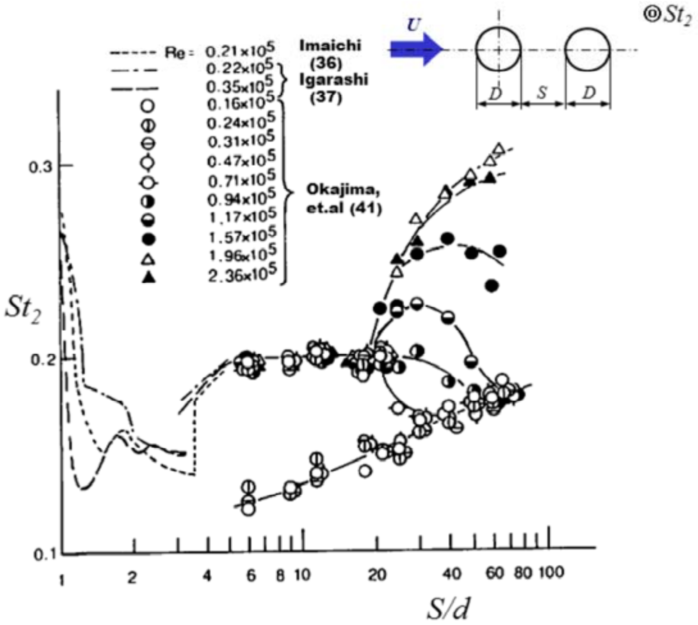
(A) L/D = 6



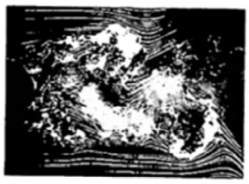
(B) L/D = 11



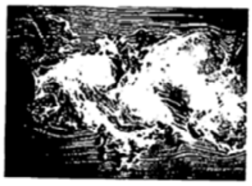
(C) L/D = 21



Strouhal numbers and wake flow patterns (Re=0.8x10^4) behind a downstream cylinder



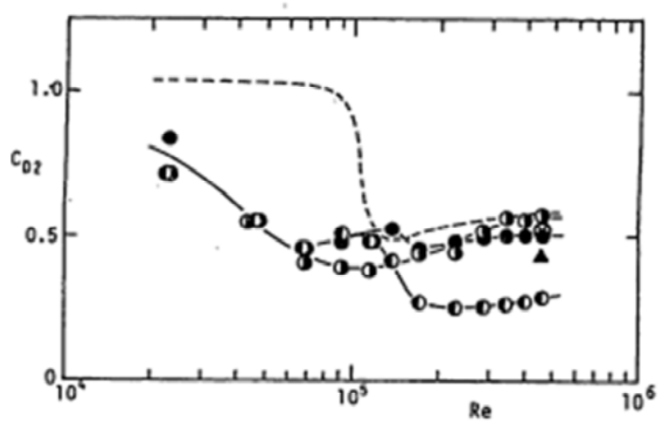
(A) L/D = 6



(B) L/D = 11

(C) L/D = 21

Re=0.8x10^4



$s/d=20$ { ○：滑面-あらさ，○：あらさ-滑面
●：あらさ-あらさ
$s/d=10$，▲：あらさ-あらさ
$s/d=29$，○：あらさ-あらさ
：上流側表面あらさ円柱の C_{D1}

図 10　直列表面あらさ円柱の抵抗

Roughed Circular Cylinders

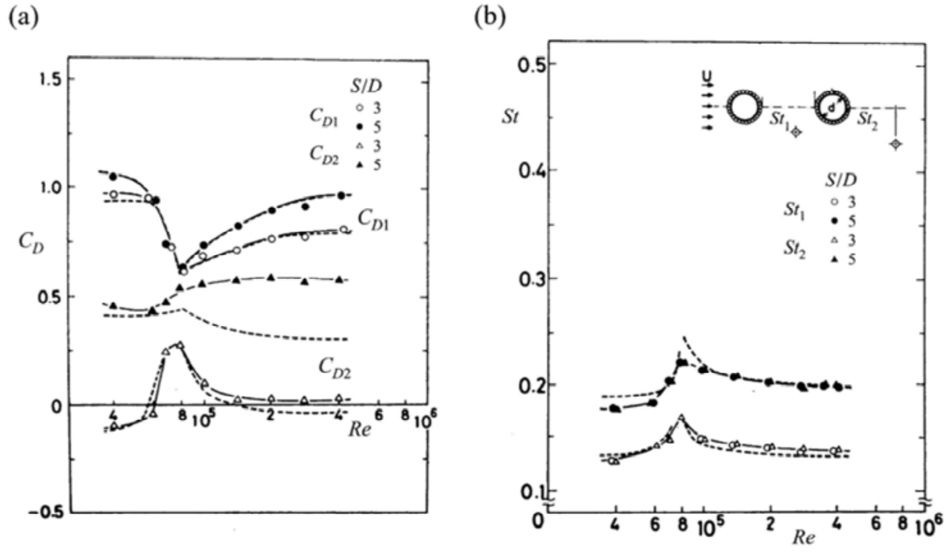
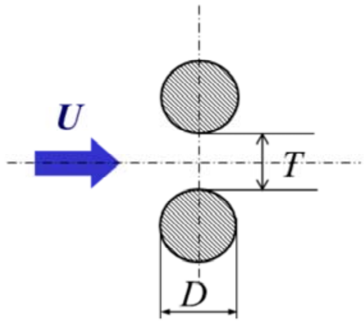


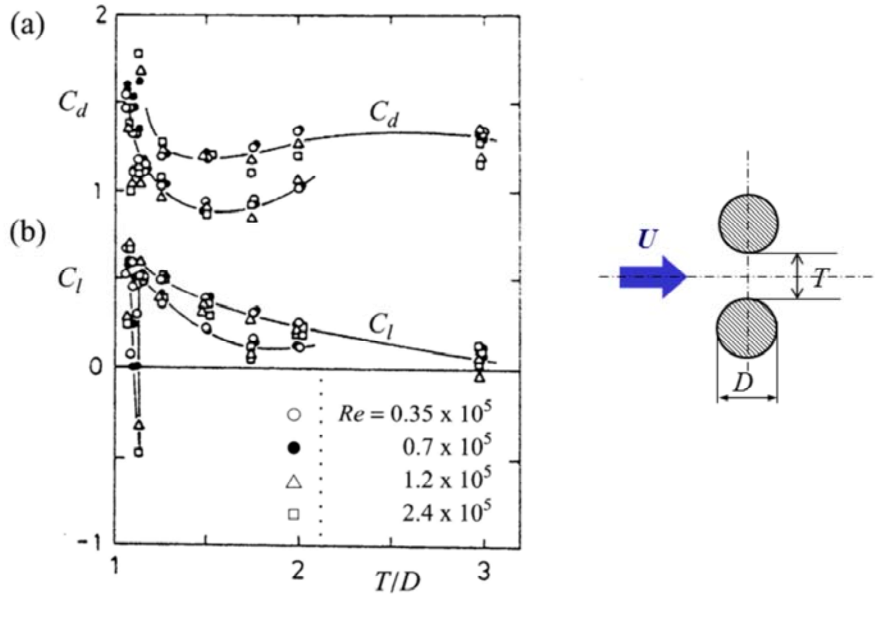
FIG. 26.24. Effect of surface roughness $K/D = 0.9\%$ in terms of Re, on (a) drag, (b) Strouhal number, Okajima (1979J)

Side by Side Cylinders in a Flow

(1) Statistic Characteristics

(2) Aeroelastic Characteristics





45. (a) Local drag, (b) local lift in terms of T/D for side-by-side cylin-
t $Re = 120\text{k}$ and 240k, Okajima *et al.* (1986J)

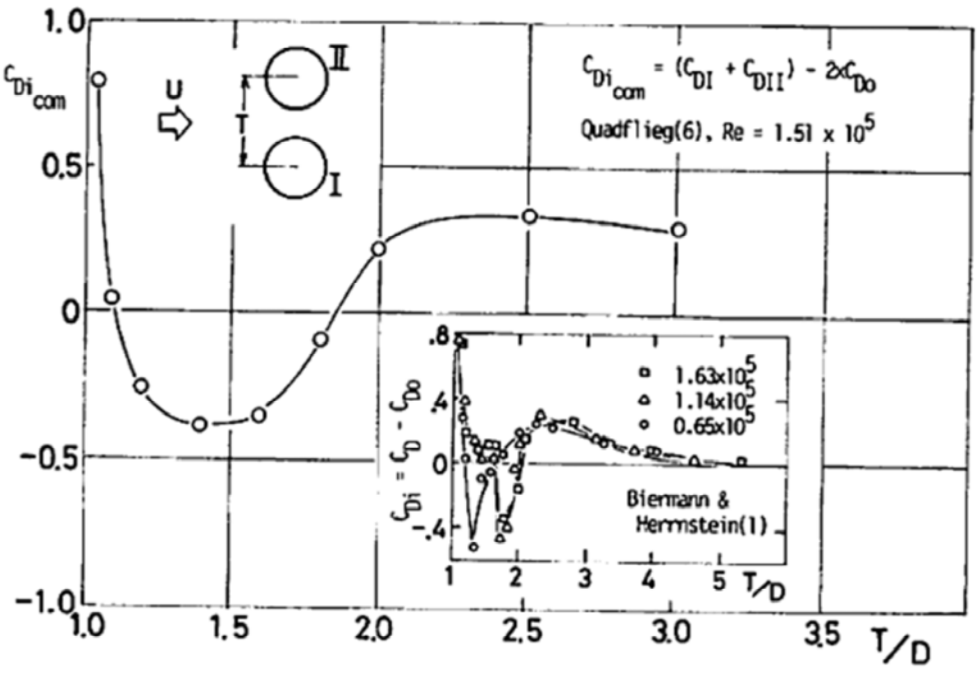
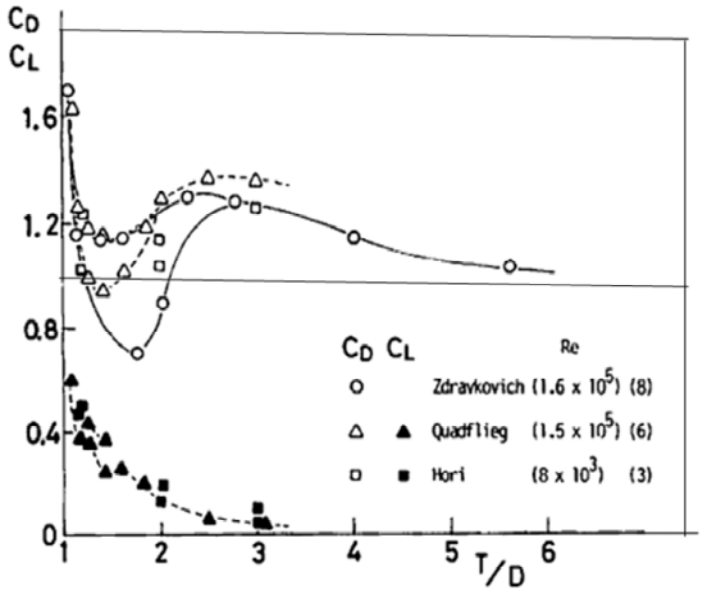
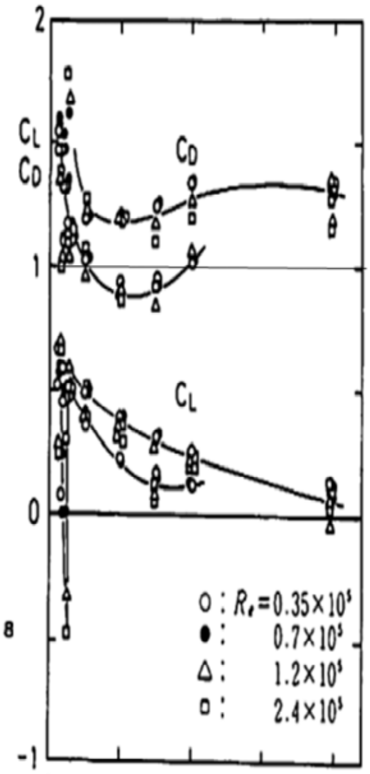
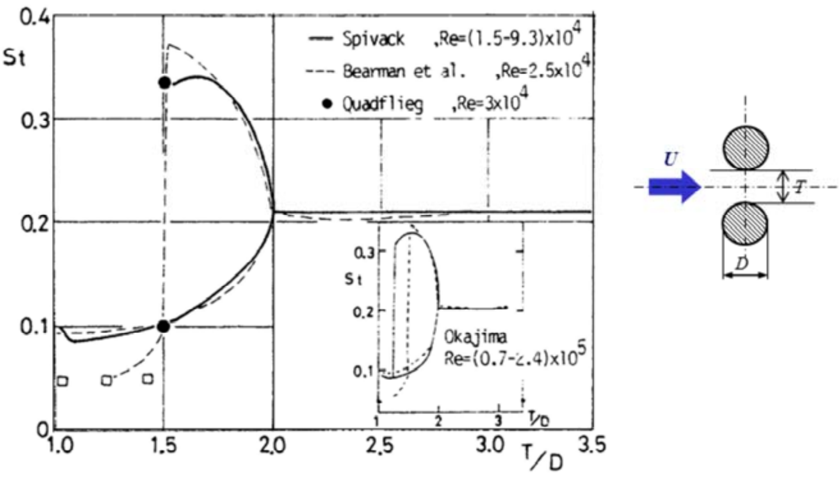


Figure 2. Interference drag coefficient of two circular cylinders in the side-by-side arrangement versus spacing ratio T/D [1, 6].

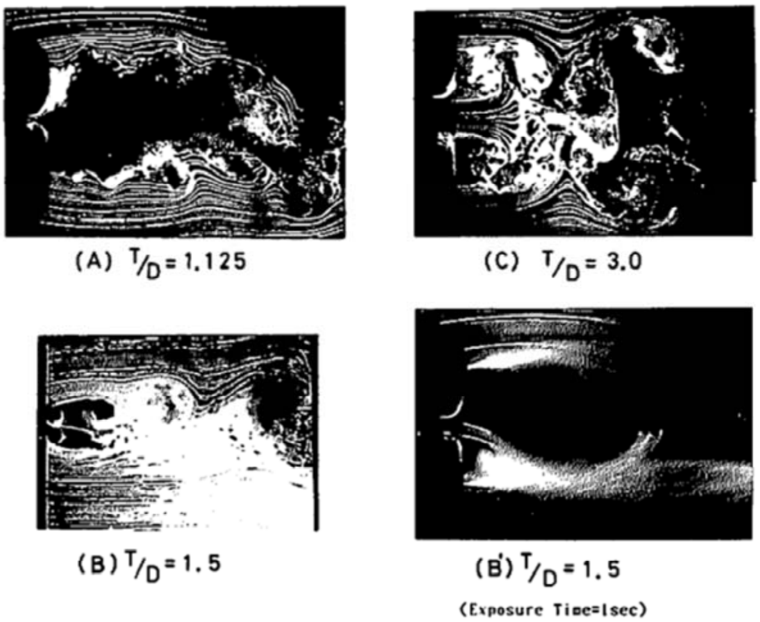


e 6. Lift and drag coefficients for the side-by-side arrangement versus T/D [3, 6, 8





G. 26.35. Strouhal number in terms of T/D, Okajima *et al.* (1986J)



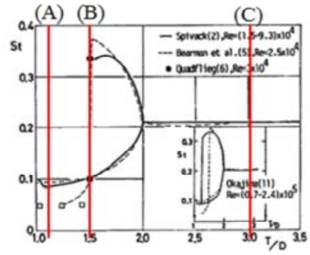


Figure 3. Strouhal number for the side-by-side arrangement versus T/D [2, 5, 6

Figure 4. Flow patterns around two circular cylinders in the side-by-side arrangement at various spacing ratios [11, 23].
(A) T/D = 1.125 (instantaneous flow).
(B) T/D = 1.5 (instantaneous flow).
(B') T/D = 1.5 (time-mean flow).
(C) T/D = 3 (instantaneous flow).

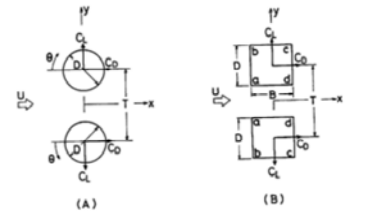


Figure 1. Side-by-side arrangement and definition of fluid force coefficients: (A) circular cylinders; (B) rectangular cylinders.

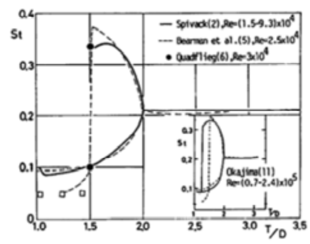


Figure 3. Strouhal number for the side-by-side

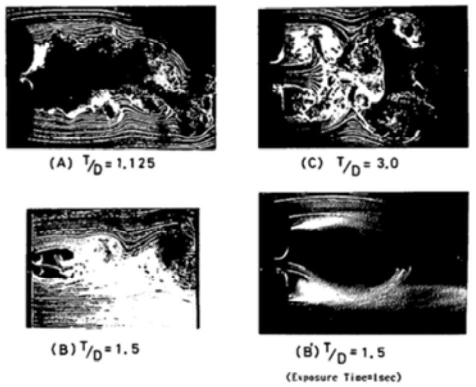


Figure 4. Flow patterns around two circular cylinders in the side-by-side arrangement at various spacing ratios [11, 23].
(A) T/D = 1.125 (instantaneous flow).
(B) T/D = 1.5 (instantaneous flow).
(B') T/D = 1.5 (time-mean flow).
(C) T/D = 3 (instantaneous flow).

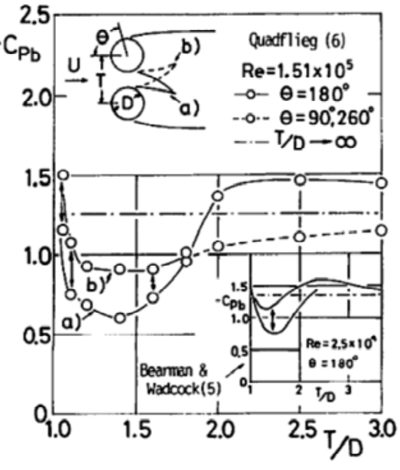


Figure
cient f
ment
dotted
single

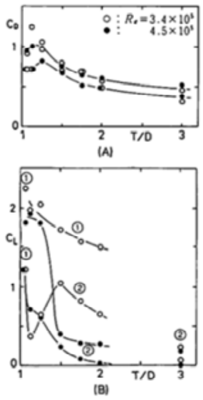


Figure 8. Lift and drag coefficients for the side-by-side arrangement at supercritical Reynolds numbers versus T/D [11].
(A) Drag coefficient.
(B) Lift coefficient. The number shows the number of separation bubbles for each cylinder.

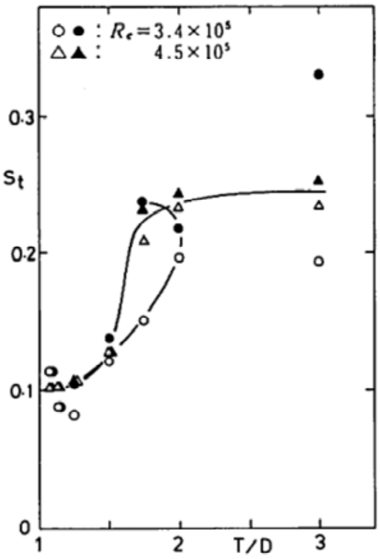
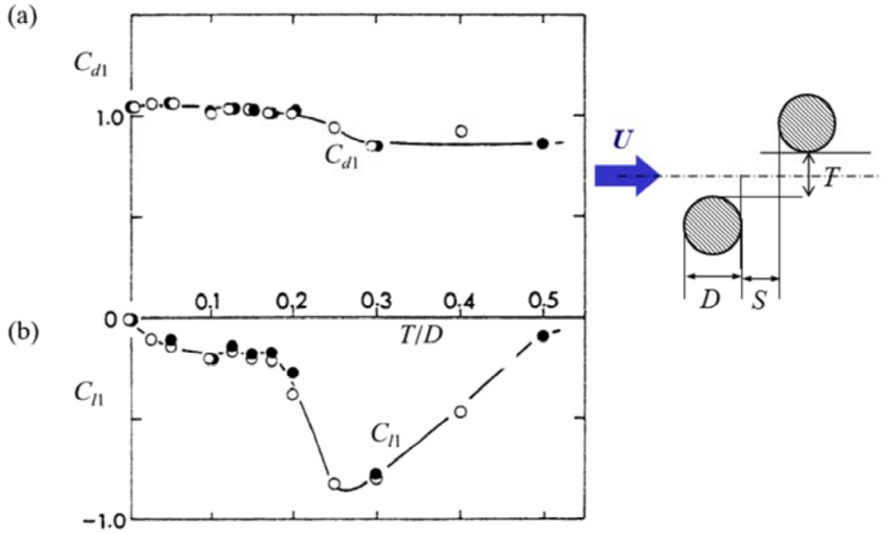


Figure 9. Strouhal num
side-by-side arrangeme
critical Reynolds numbe
[11].



6.54. Variation in local (a) drag, (b) lift in terms of T/D for $S/D = 1.25$
$Re = 100$k, Okajima and Sugitani (1976P)

Conference on Modelling Fluid Flow (CMFF -6)
The 13th International Conference on Fluid Flow Technologies
Budapest, Hungary, September 6-9, 2006

Flow-Induced In-Line Oscillation of Two Circular Cylinders in Tandem Arrangement

Atsushi OKAJIMA,
Professor, Kanazawa-Gakuin College
and
Satoru YASUI, Takahiro KIWATA, and Shigeo KIMURA

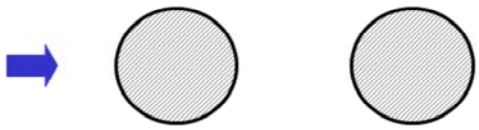
***Keywords*: flow-induced oscillation, in-line oscillation, two circular cylinders, tandem arrangement, flow visualization**

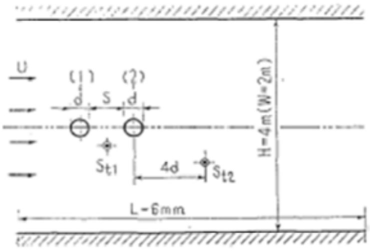
I would like to talk about Flow-Induced In-Line Oscillation of Two Circular Cylinders in Tandem Arrangement.

Two Tandem Cylinders

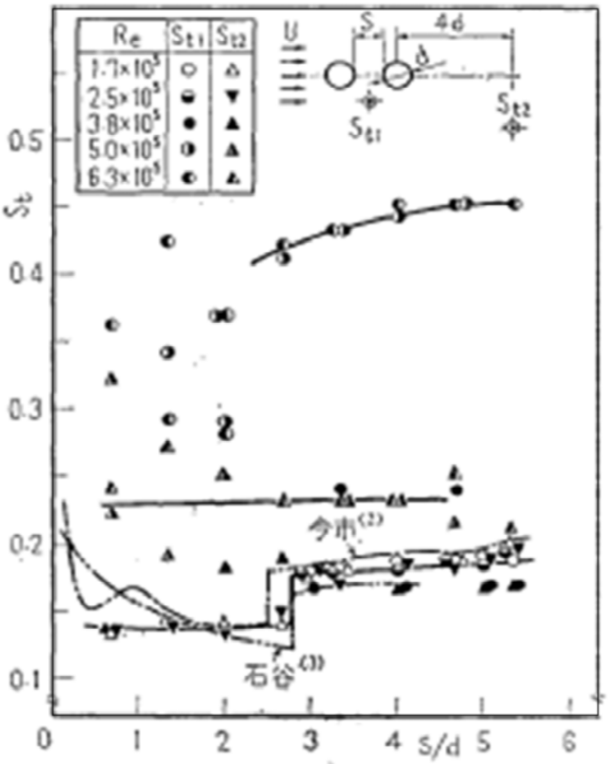
(1) Statistic Characteristics of High Reynolds Numbers

(2) Aeroelastic Characteristics



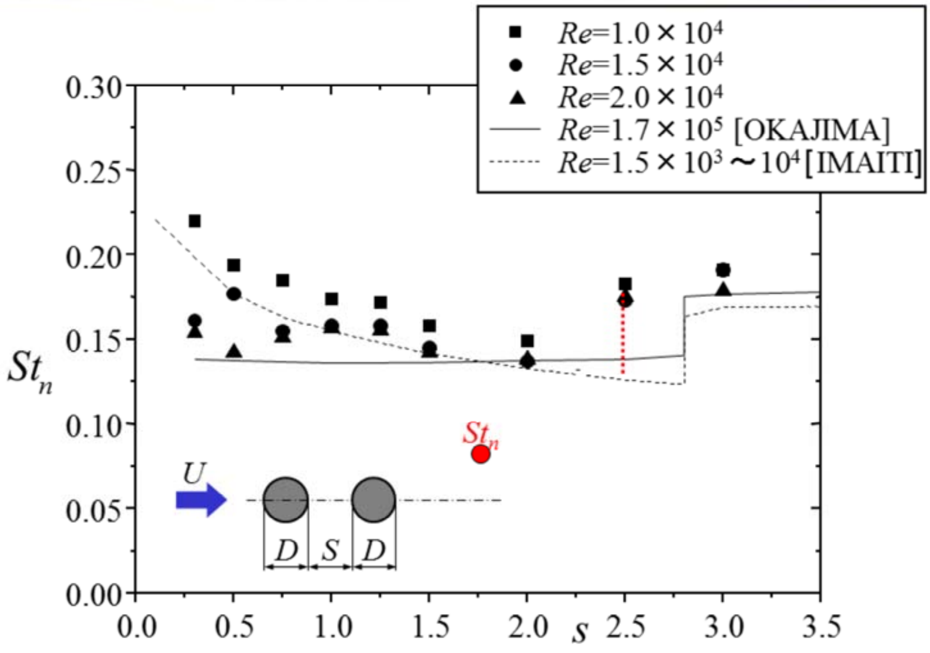


滑面直列2本円柱の配置概略



隙間S/dに対する滑面直列2本円柱の抵抗St_1,St_2

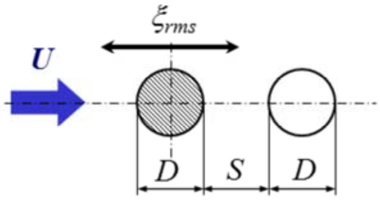
FUNDAMENTAL DATA : Strouhal Numbers of Two Stationary Cylinders in Tandem Arrangement



Strouhal number changes with spreading the gap-distance and is influenced by Reynolds number

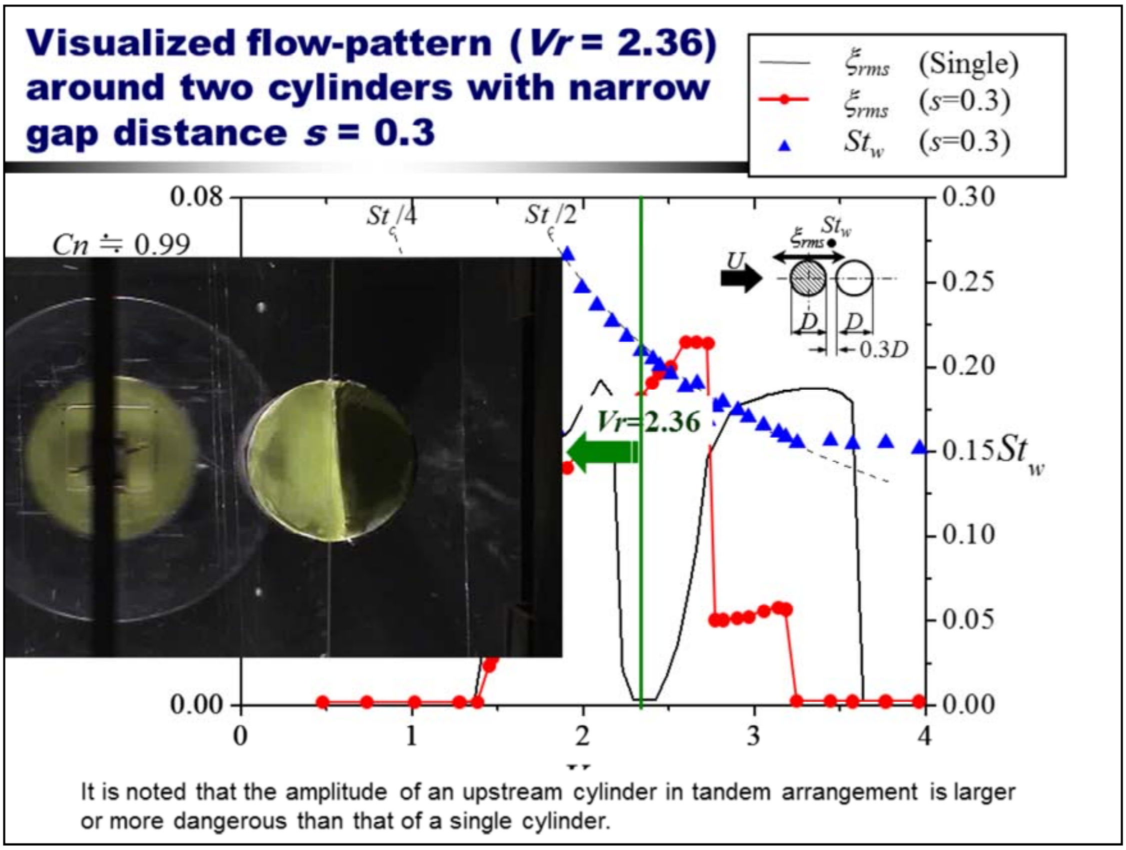
(6) And also we show the results of the Strouhal number behind two stationary cylinders in tandem arrangement against the gap-distance as the fundamental data of two tandem cylinders. You can see that the Strouhal number changes with spreading the gap-distance and is influenced by Reynolds number, also.

RESULTS: Flow-Induced In-Line Oscillation of the Upstream Cylinder

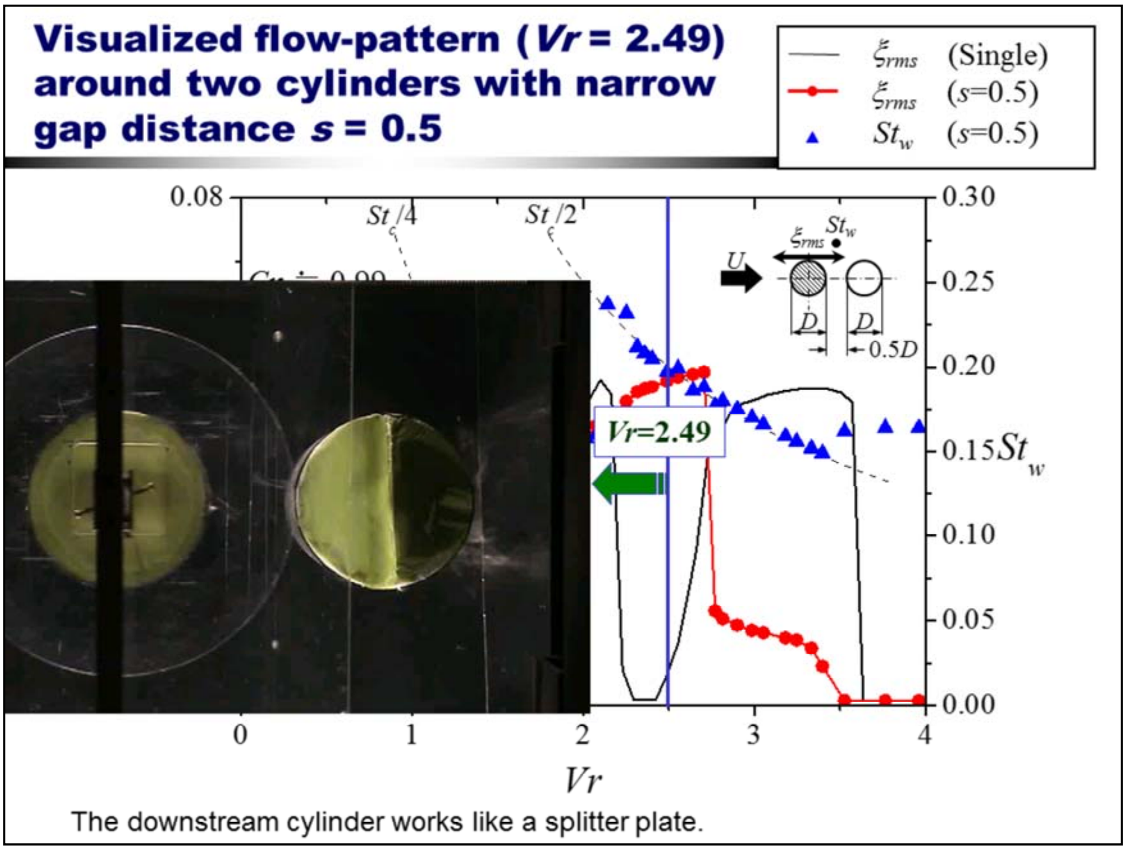


The upstream cylinder is free for in-line oscillation and the downstream cylinder is fixed.

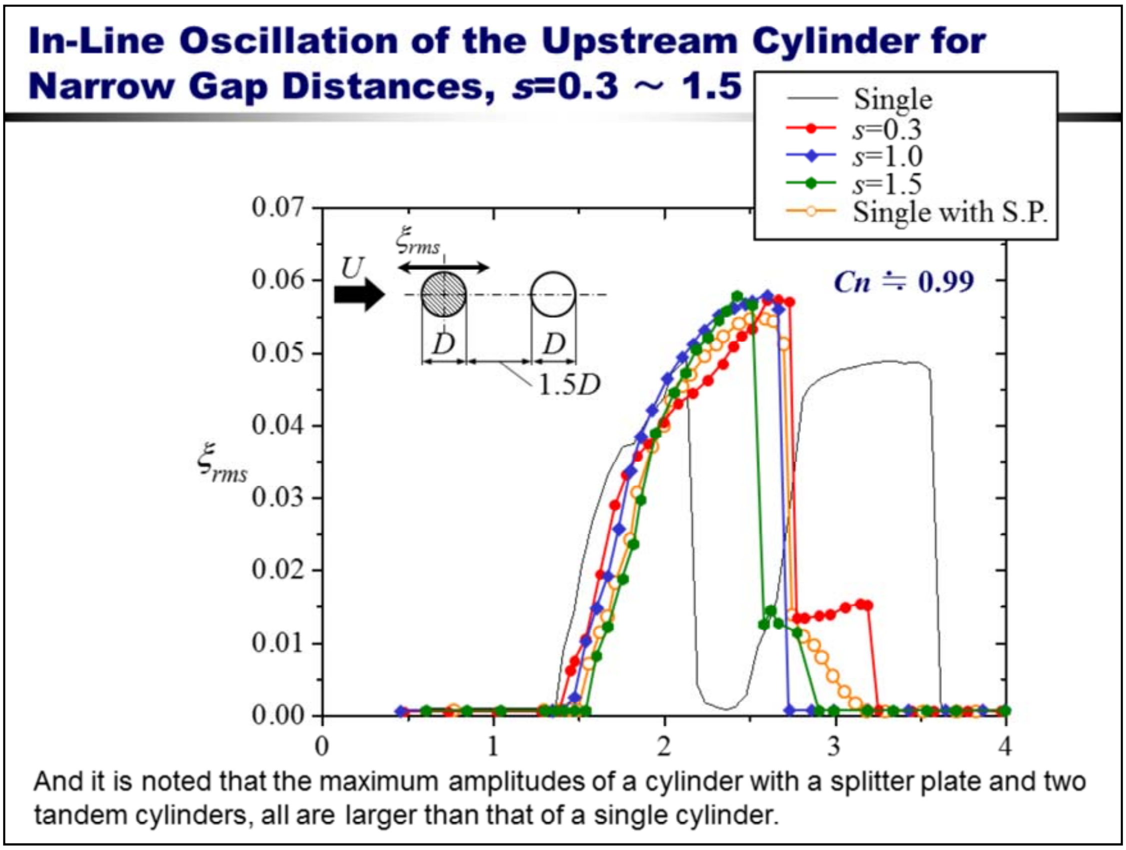
(8) Well we present experimental results when the upstream cylinder is free for in-line oscillation and the downstream cylinder is fixed.



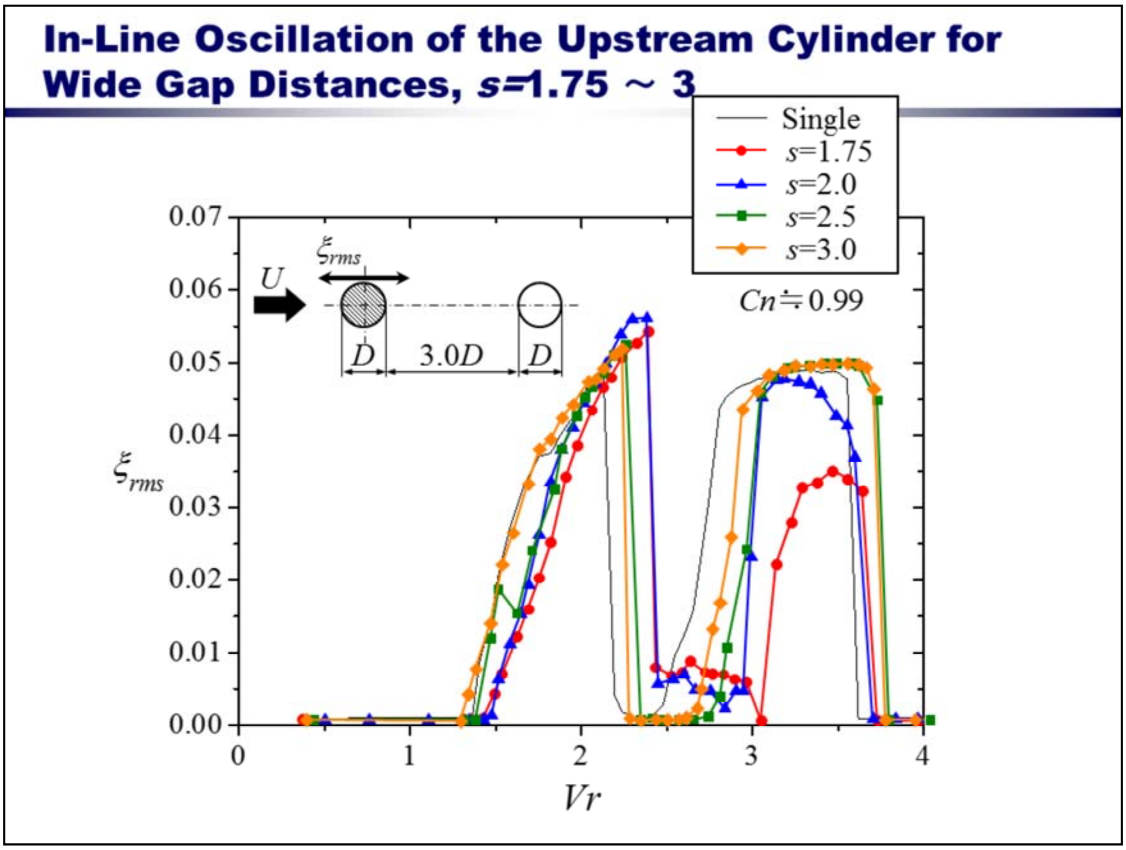
(9) This figure shows an example of the response curve of the in-line oscillation of the upstream cylinder for the narrow gap distance of 0.3. This figure shows response amplitude and the Strouhal number of a wake against reduced velocity, compared with the results for a single cylinder. You will find only one excitation region, which is different from two excitation regions for a single cylinder. We present a visualized animation for the upstream cylinder oscillating at reduced velocity 2.36, You can see, the shear layer separating from the upstream cylinder clearly rolls up into symmetrical vortices in the gap-field. It is evident that this in-line oscillation is induced by the symmetric vortices formed in the gap-field.



(10) This figure also shows another example of the response curve and the Strouhal number of the upstream cylinder oscillating for the narrow gap distance of 0.5. You can see a single excitation region like this. And we present a visualized animation for the upstream cylinder oscillating at reduced velocity 2.49. It is evident that this in-line oscillation is induced by the symmetric vortices formed in the gap-field.

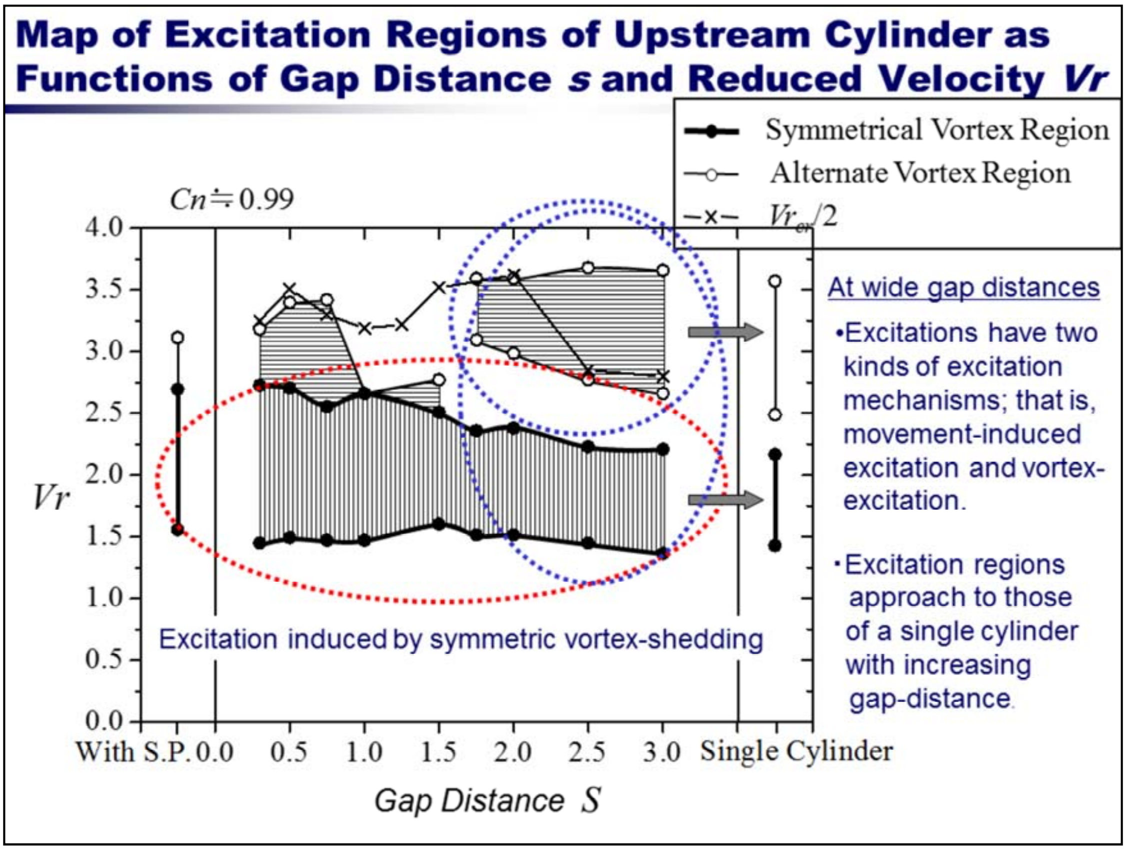


(11) This figure summarizes the response characteristics of the in-line oscillation of the upstream cylinder for the narrow gaps from 0.3 to 1.5. This is the response curve of a single cylinder. This is for a cylinder having a splitter plate. The gap distance changes into 0.3, 0.5, 1.0 and 1.5. You can see all response curves are similar to the response-characteristics of a cylinder with a splitter plate. It means that downstream cylinder works as a splitter plate.



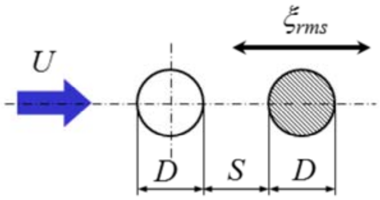
(12)The response curves for the wide gap distances from 1.75 to 3 are presented here.

It is evident that all the response curves gradually approach that of a single cylinder with spreading gap distance over 1.75.



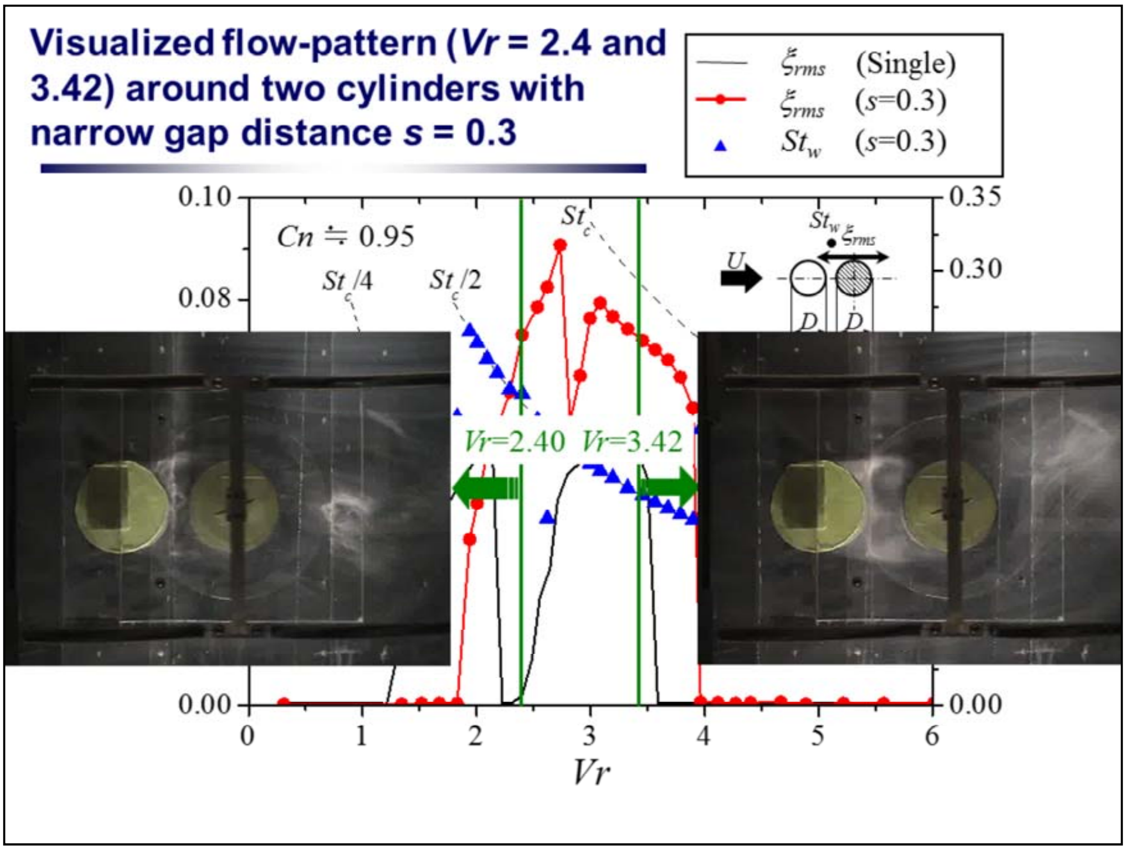
(13) Then we try to make a map of excitation regions of the upstream cylinder as functions of gap distance and reduced velocity. We can see two kinds of excitation regions due to different oscillation mechanisms; that is, symmetric vortices and alternate vortices. Excitation induced by symmetric vortex-shedding appears at all experimental gaps. The excitation of the upstream cylinder with wide gap have two kinds of excitation mechanisms; that is, movement-induced excitation and vortex-excitation. These characteristics approach to that of the single cylinder with increasing gap-distance over 1.75.

RESULTS : Flow-Induced In-Line Oscillation of the Downstream Cylinder

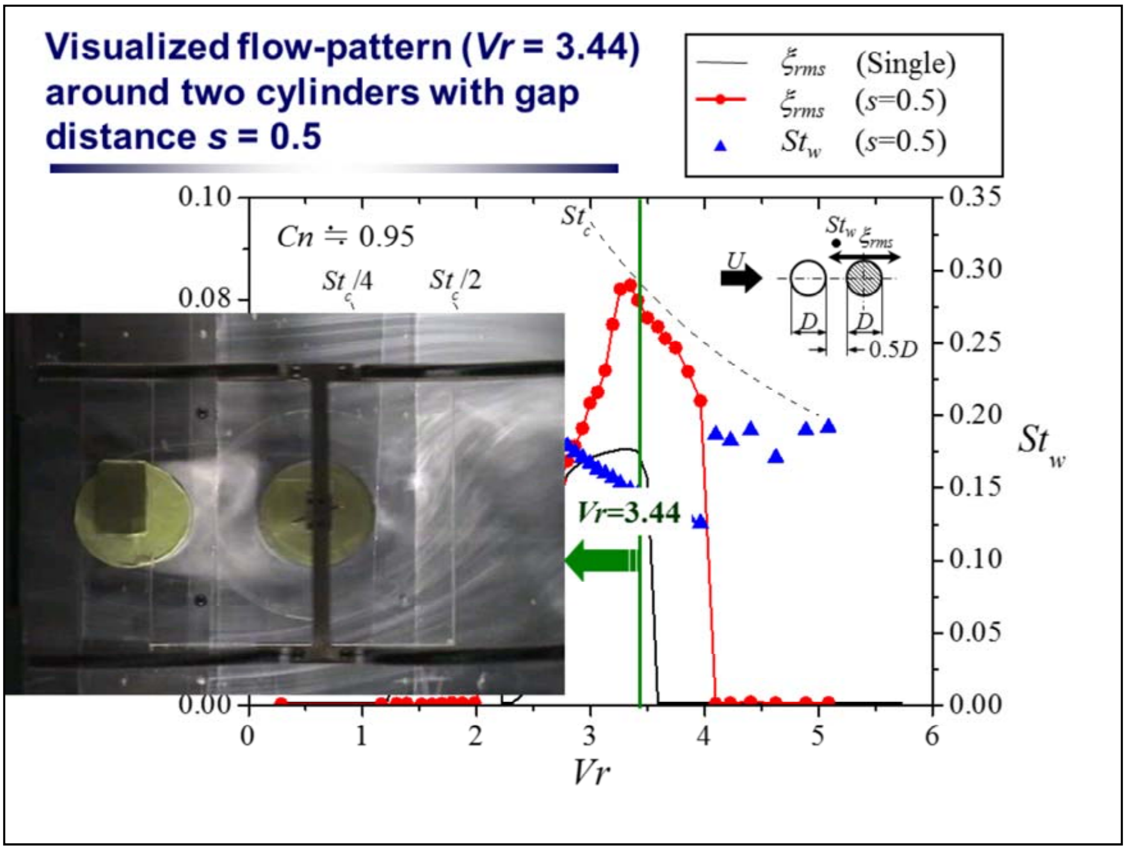


The downstream cylinder is free for in-line oscillation and the upstream cylinder is fixed.

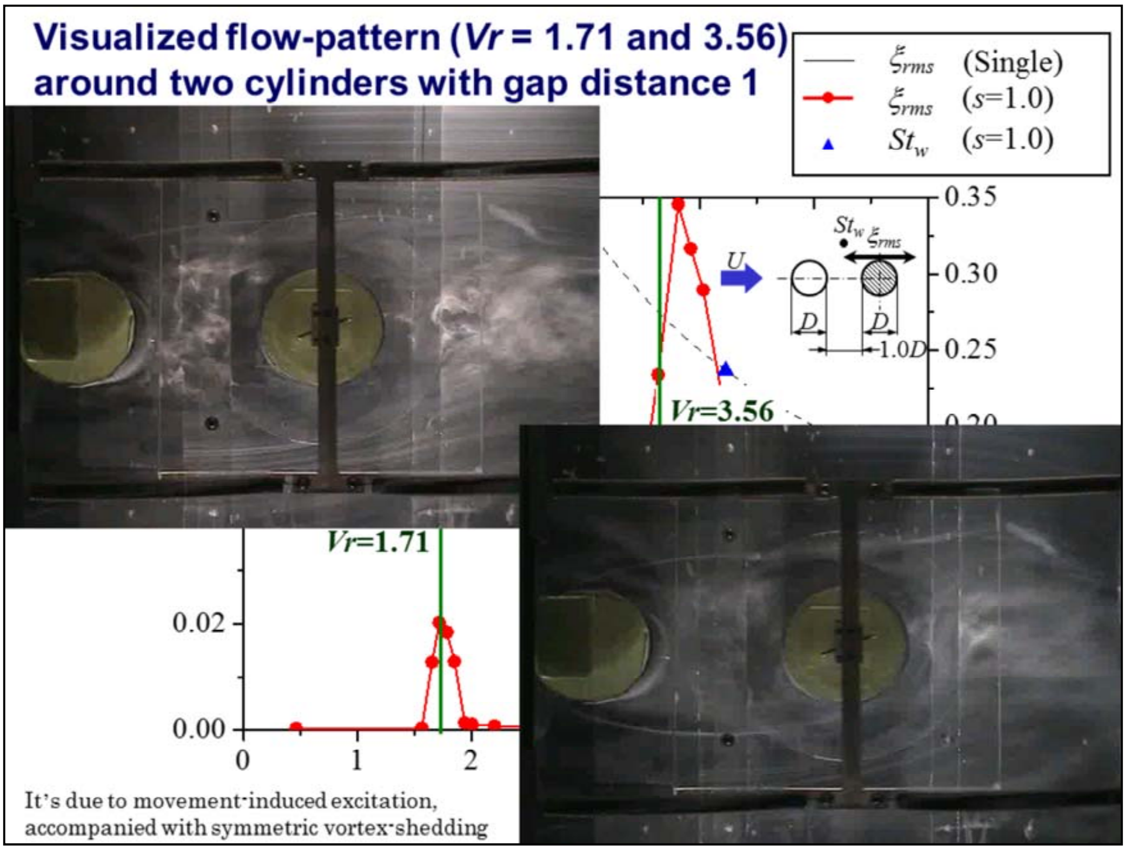
(14) Next we present the results when the downstream cylinder is free for in-line oscillation and the upstream cylinder is fixed.



(15)This figure shows the response curve and Strouhal numbers of the downstream cylinder with narrow gap distance ratio of 0.3. The response characteristics has two kinds of excitation regions, so we show visualized animation of the downstream cylinder oscillating at reduced velocity of 2.4. You can see an oscillation of the downstream cylinder induced by a symmetric vortex-shedding. And we show the other visualized pictures at different and high velocity of 3.42. At this velocity, it's certified that a downstream cylinder oscillates due to the alternate Karman vortex shedding.

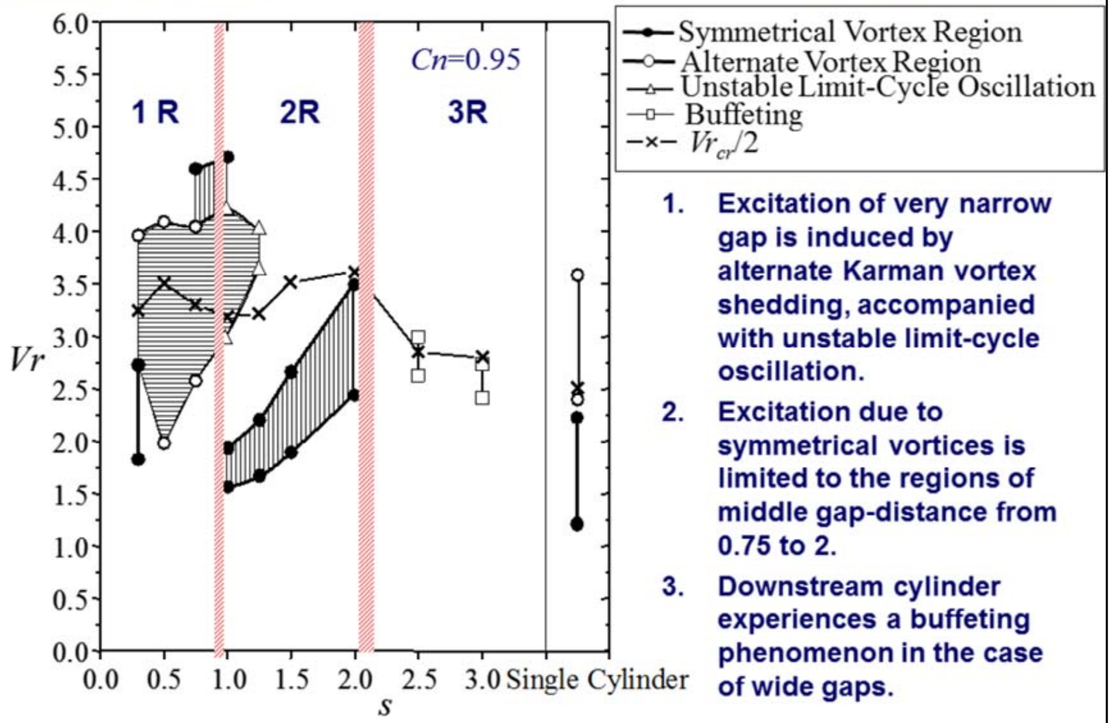


(16)We show the response curve and Strouhal numbers of the downstream cylinder with narrow gap of 0.5, also and a visualized animation at the reduced velocity of 3.44. In this figure, a downstream cylinder oscillates with half the Strouhal frequency, locking to alternate Karman vortex shedding.



(17)You will note that the response curve of the downstream cylinder with middle gap distance of 1, has two excitation regions; that is, the reduced velocities are from 1.5 to 2 and from 3 to 5. You will find that the excitation of small amplitude at low reduced velocity of 1.71, is due to the movement-induced excitation, accompanied with symmetrical vortex-shedding. On the other hand, the animation at high velocity 3.56 shows that this excitation with a large amplitude is induced by alternate Karman vortex shedding like this.

Map of Excitation regions of downstream cylinder as functions of gap distance *s* and reduced velocity *Vr*



1. Excitation of very narrow gap is induced by alternate Karman vortex shedding, accompanied with unstable limit-cycle oscillation.
2. Excitation due to symmetrical vortices is limited to the regions of middle gap-distance from 0.75 to 2.
3. Downstream cylinder experiences a buffeting phenomenon in the case of wide gaps.

(18)Finally, excitation regions of the downstream cylinder are mapped against gap distance and reduced velocity. We classify the excitation region as three regions, namely,

1R:Excitation of very narrow gap is induced by alternate Karman vortex shedding accompanied with unstable limit-cycle oscillation.

2R:Excitation due to symmetrical vortices is limited to the regions of middle gap-distance from 0.75 to 2.

3R:Downstream cylinder experiences a buffeting phenomenon in the case of wide gap over 2.

CONCLUSIONS

Flow-induced in-line oscillation of two tandem circular cylinders was experimentally studied by free-oscillation testing in a wind tunnel. We carried out two kinds of free-oscillation tests of two tandem cylinders. We measured the response amplitudes and the Strouhal frequency as functions of the gap distance. The flow around the cylinders was visualized by the smoke-wire method, also.

(1) The in-line oscillation induced by symmetric vortex shedding of the upstream cylinder appears in all experimental ranges of gap.
At wide gap-ratios *s* = 2 to 3, the other excitation of *Vr* = 3 to 3.5 is induced by alternate Karman vortex shedding like a single cylinder.

(2) The in-line excitation of the downstream cylinder is confirmed to be induced by alternate Karman vortex shedding for the narrow gap distances *s* = 0.3 to 0.75, and the other excitation due to symmetric vortices are limited to gap distances of *s* = 0.75 to 2.
Furthermore, the downstream cylinder experiences a buffeting phenomenon by wake-fluctuation of the upstream cylinder, when the gap distance is greater than 2.5.

(19)Flow-induced in-line oscillation of two tandem circular cylinders was experimentally studied by free-oscillation testing in a wind tunnel. We carried out two kinds of free-oscillation tests of two tandem cylinders.

(1) The in-line oscillation induced by symmetrical vortex shedding of the upstream cylinder appears in all experimental range of a gap.
At wide gap-ratios *s* = 2 to 3, the other excitation of *Vr* = 3 to 3.5 is induced by alternate Karman vortex shedding like a single cylinder.
(2) The in-line excitation of the downstream cylinder is confirmed to be induced by alternate Karman vortex shedding for the narrow gap distance *s* = 0.3 to 0.75, and the other excitation due to symmetrical vortices are limited to gap distance ratios *s* = 0.75 to 2.

Furthermore, the downstream cylinder experiences a buffeting phenomenon by wake-fluctuation of the upstream cylinder, when the gap distance is greater than $s = 2.5$.

2007 ASME Pressure Vessels and Piping Division Conference
July 22-26, 2007, San Antonio

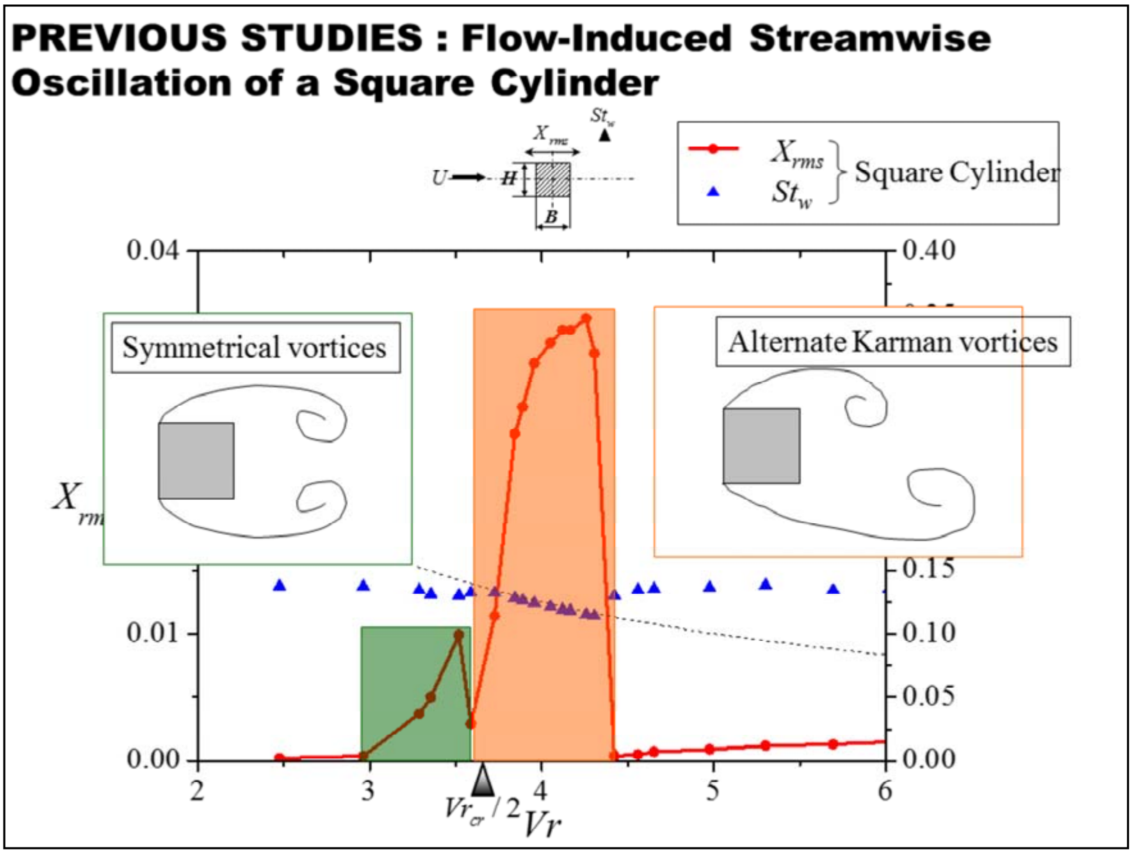
FLOW-INDUCED STREAMWISE OSCILLATION OF TWO SQUARE CYLINDERS IN TANDEM ARRANGEMENT

Atsushi OKAJIMA,
Professor, Kanazawa-Gakuin College
and
Takahiro KIWATA, Satoru YASUI, Yoshiki MORI, Shigeo KIMURA

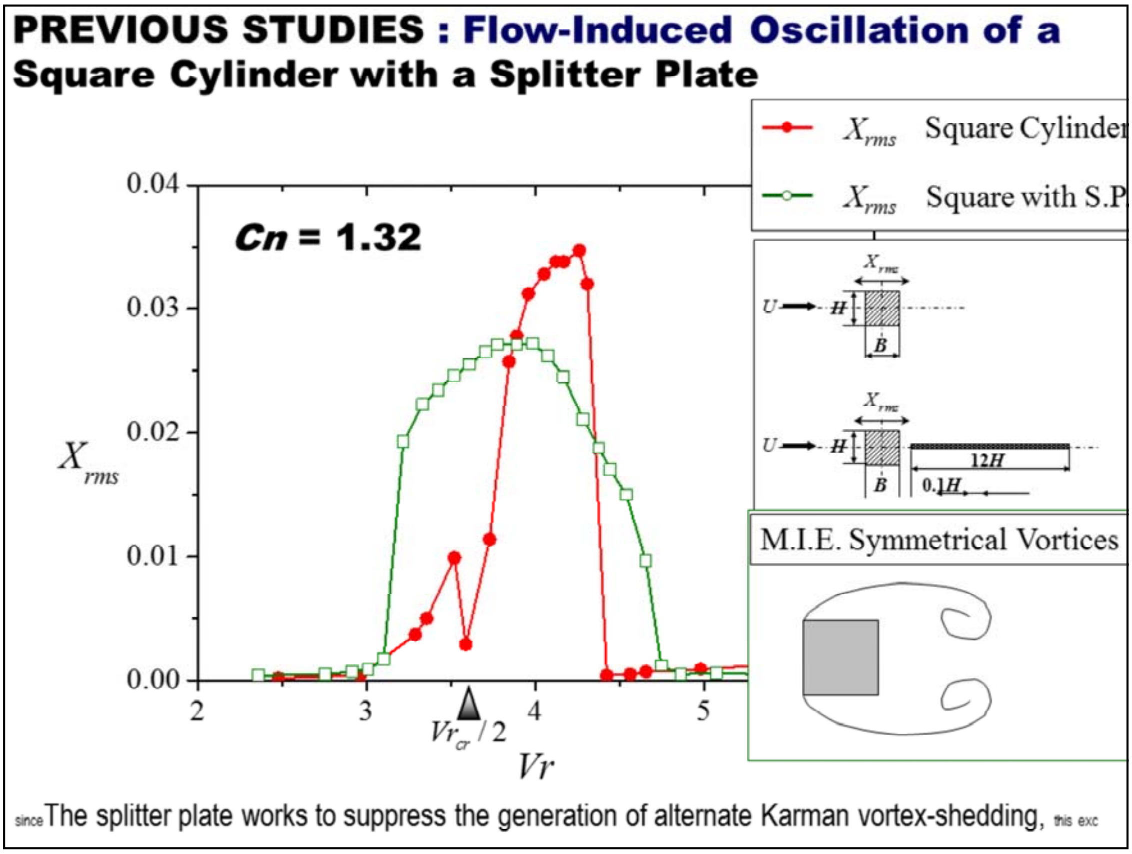
Keywords: **flow-induced oscillation, streamwise oscillation, two square cylinders, tandem arrangement, flow visualization**

(1) Thank you, Mr. Chairman.

I would like to talk about flow-induced streamwise oscillation of two square cylinders in tandem arrangement.



(2) As fundamental information, I'll show you results of response amplitude for a single square cylinder obtained by the previous studies. The streamwise oscillations occur in two regions near half of the resonance velocity; the one at lower velocity is termed the first excitation region due to symmetrical vortices, and the other excitation at high velocities is termed the second excitation region due to alternate Karman vortices.



(3) When we insert a splitter plate in the wake of a square cylinder, the response amplitudes of the streamwise oscillation are plotted with the green line. Since the splitter plate works to suppress the generation of alternate Karman vortex-shedding, this excitation is apparently due to the movement-induced excitation accompanied by symmetrical vortices.

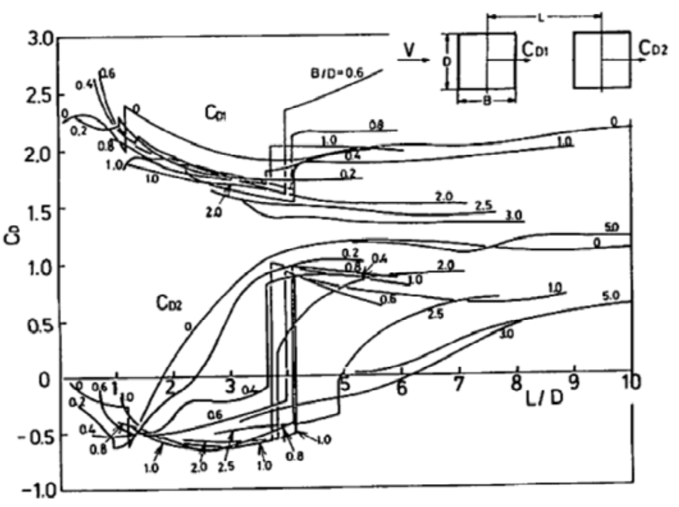
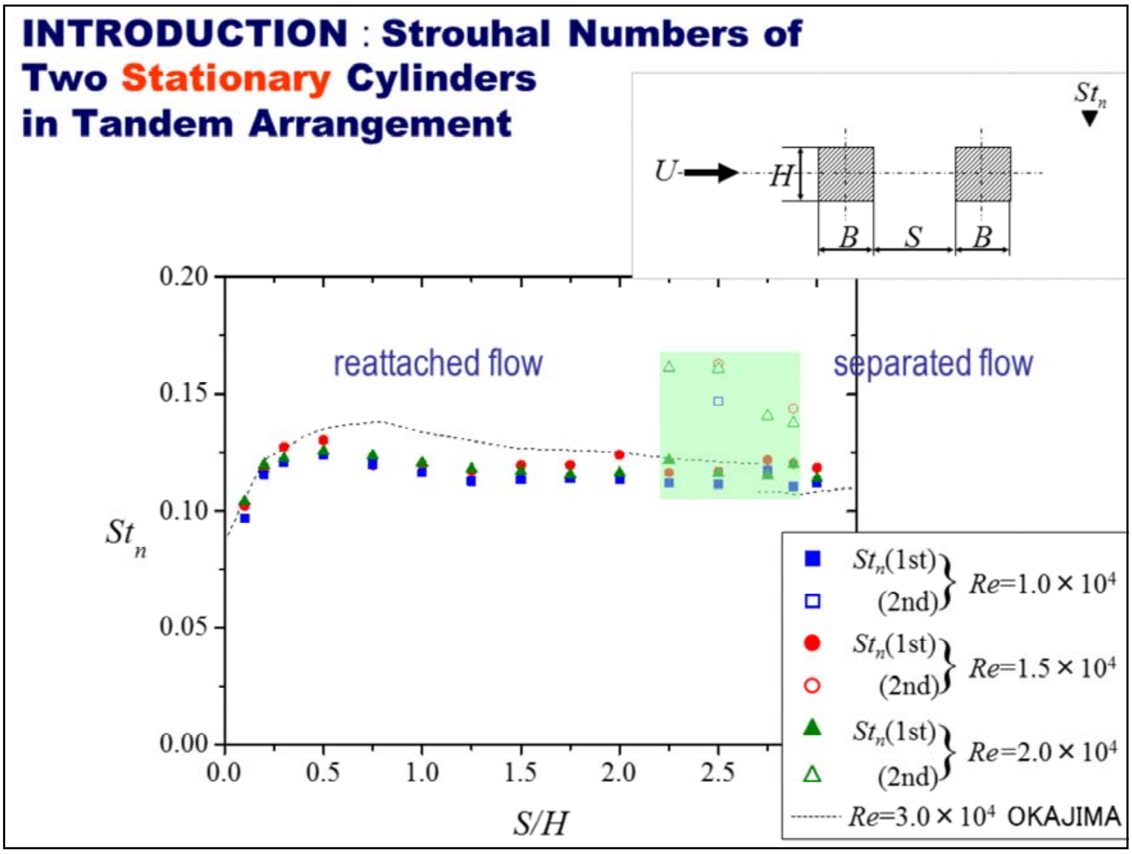


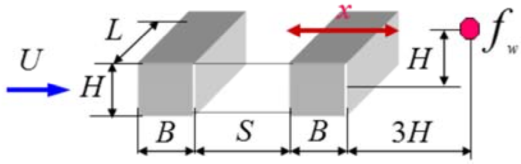
Figure 37. Drag coefficients of two tandem rectangular cylinders with various side ratios, B/D, of 0, 0.2, 0.4, 0.6, 0.8, 1.2, 2.5, 3, and 5 [28, 51, 52].



(4) We show the results of the Strouhal number behind two stationary cylinders in tandem arrangement against the gap-distance as the fundamental data of two tandem cylinders. You can see that the Strouhal number changes with spreading the gap-distance. The values of the Strouhal number seem to be close, slightly influenced by the Reynolds number. Only at these gap distances, the values of Strouhal number scatter, since the flow pattern changes from a reattached flow to a separated flow.

PARAMETERS FOR FLOW-INDUCED OSCILLATION

Reduced velocity	$Vr = \frac{U}{f_c H}$
Critical reduced velocity	$Vr_{cr} = \frac{U}{f_n H}$
Reduced mass-damping parameter	$Cn = \frac{2m\delta}{\rho H^2 L}$
Non-dimensional gap distance between two cylinders	$s = \frac{S}{H}$
Non-dimensional response amplitude of a cylinder	$X_{rms} = \frac{x_{rms}}{H}$
Strouhal Number of Vortex-Shedding	$St_w = \frac{f_w H}{U}$



H : Cylinder height

f_c : Characteristic frequency of a cylinder

f_n : Natural vortex shedding frequency for a stationary cylinder

f_w : Frequency of a wake

L : Span length of a cylinder

m : Mass of a cylinder per unit span length

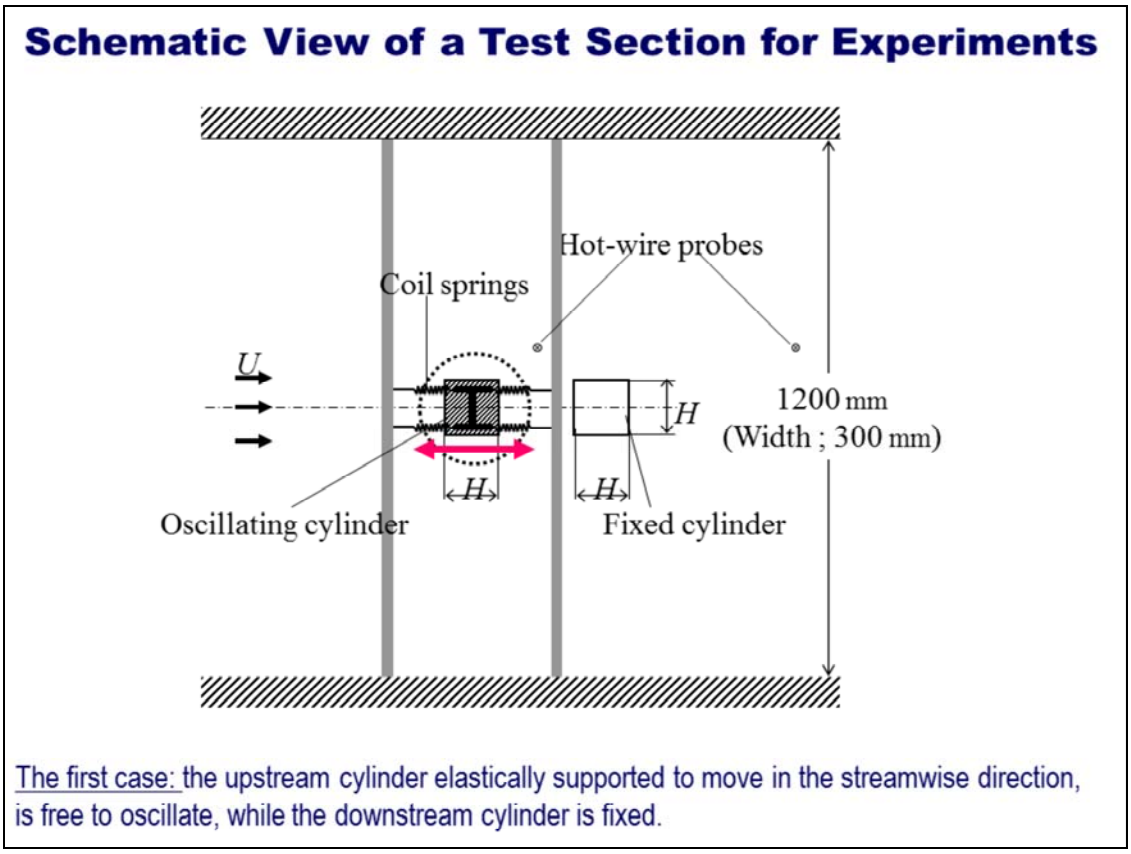
U : Uniform flow velocity

x_{rms} : Root-mean square response amplitude of a cylinder

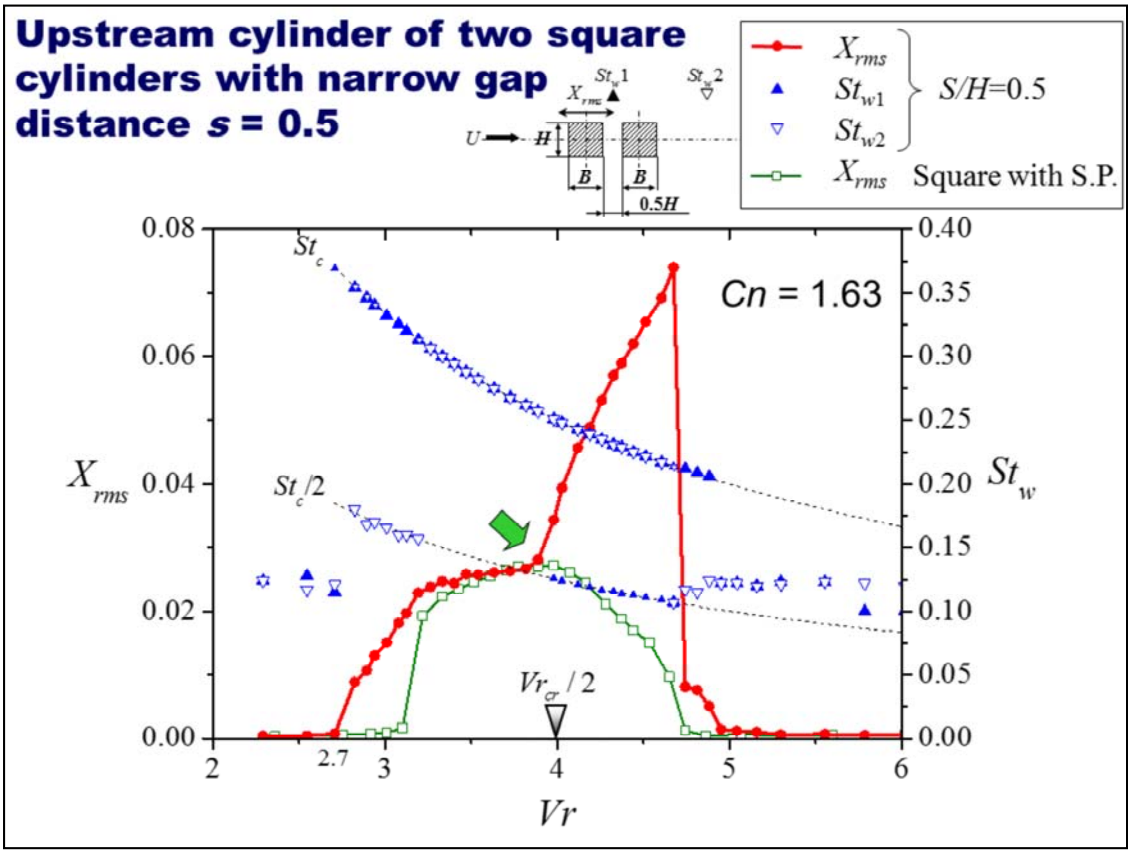
δ : Logarithmic decrement of the structure damping parameter of a cylinder

ρ : Fluid mass density

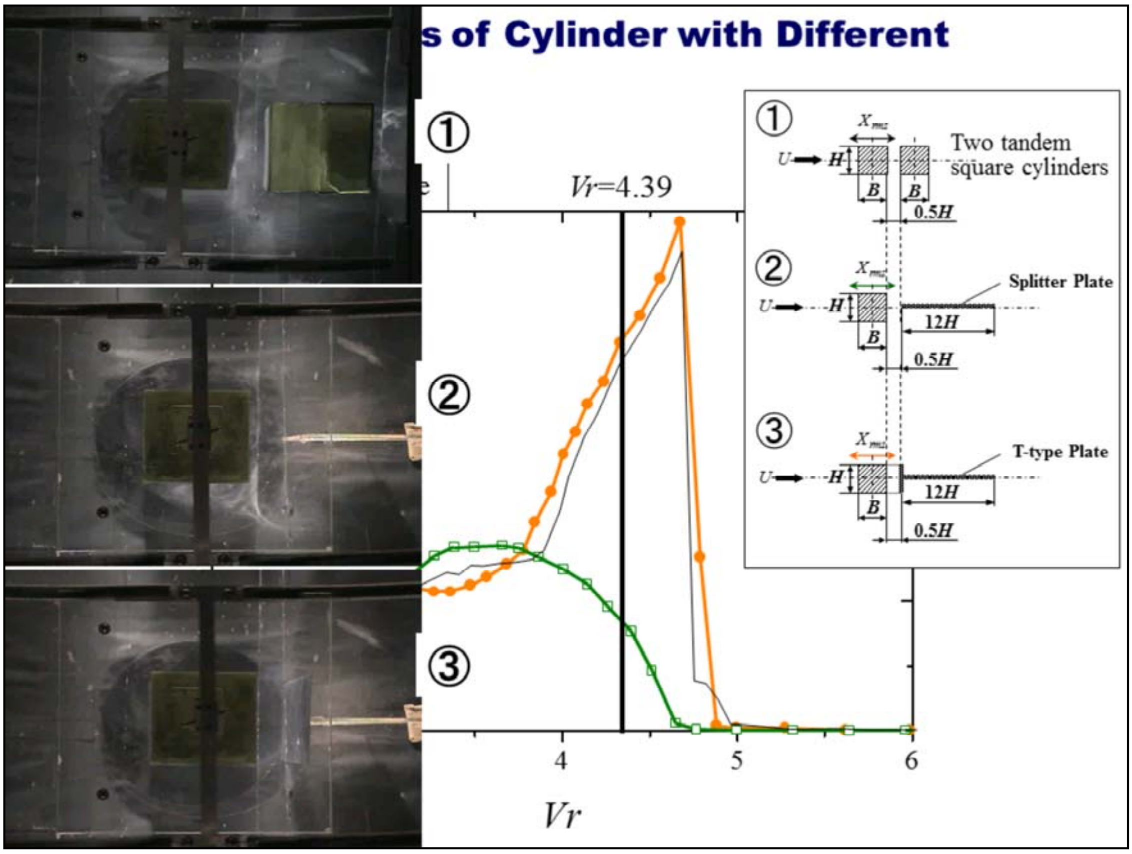
(5) When we carried out free-oscillation tests of two square cylinders in tandem arrangement, the reduced velocity, the critical reduced velocity, the reduced mass-damping parameter *Cn* and the gap distance *S* between the upstream and downstream cylinders, are important parameters.So we measured the non-dimensional response amplitudes and Strouhal number of the vortex-shedding as the experimental results.



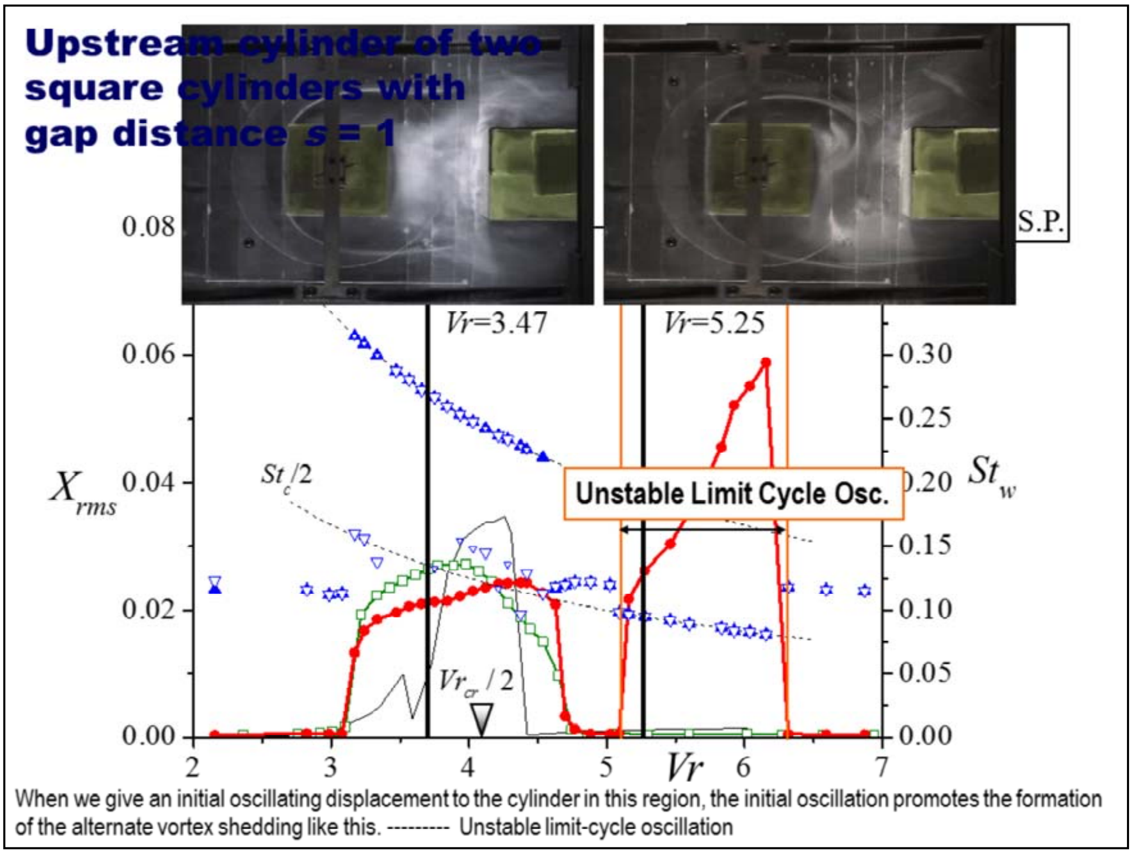
(6) Well I'll show a schematic view of a test section for experiments: In this case, the upstream cylinder elastically supported to move in the streamwise direction, is free to oscillate, while the downstream cylinder is fixed.



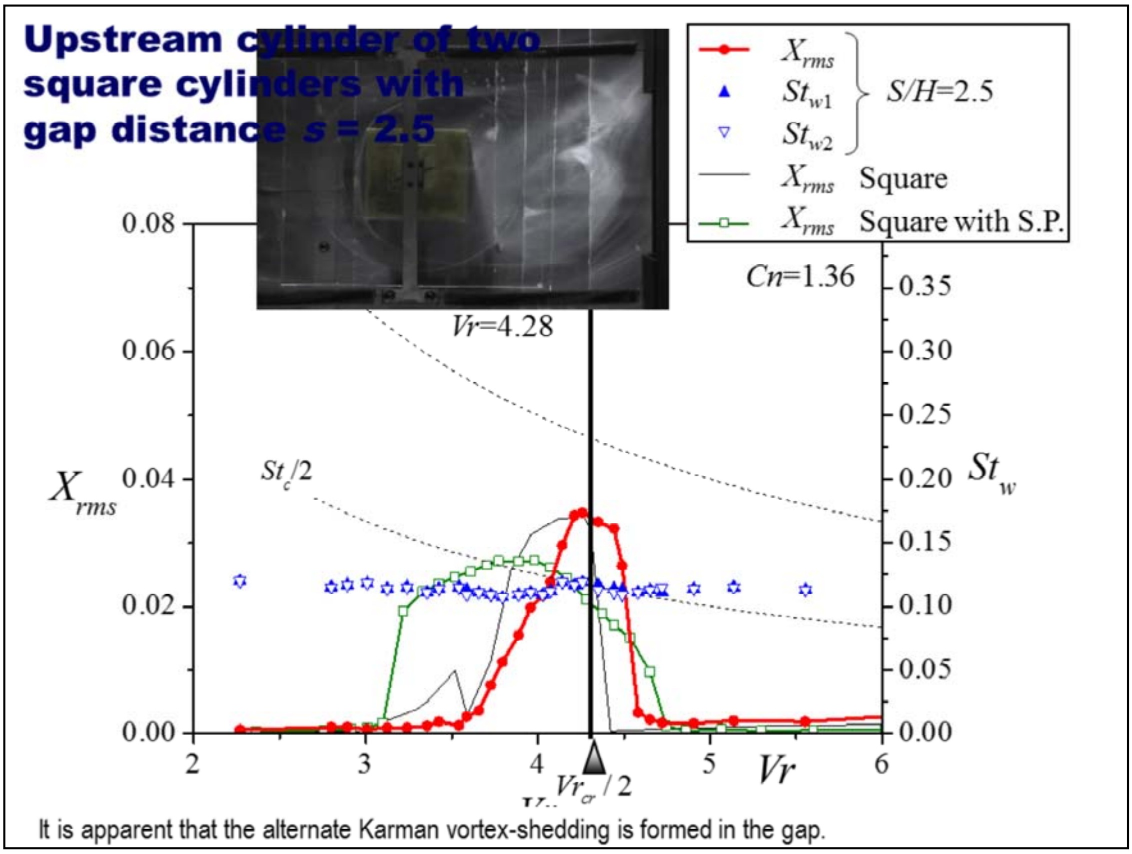
(7) I'll show an example of the response curve of the streamwise oscillation of the upstream cylinder for narrow gap distance 0.5. Streamwise oscillations begin to occur near *Vr* = 2.7, and the amplitude changes along the curve of the cylinder with a splitter plate with increasing the reduced velocity, and still the value of amplitude abruptly grows up to a maximum value of about 0.08. It is noted that this response curve is quite different from that of the cylinder with a splitter plate for this region. Why this excitation occurs, having very large amplitudes.



(8) Then we tried to curry out some additional experiments: (1) This response curve is for the case of two tandem cylinders. This curve is for the case of inserting a splitter plate, and when we employed a T- type splitter, this curve is very similar with that of two tandem cylinders. So, I'll show the visualized animations for each case: It is evident that the flows of case 1 and 3 seem to be almost similar, and you can see the wake approaches the side surfaces of the downstream cylinder or the edges of T- type splitter, which produces a narrow wake, while you can see the symmetrical vortices of the case 2 is comparatively wide. However, the excitation of all cases is due to movement-induced excitation accompanied by the symmetrical vortices.

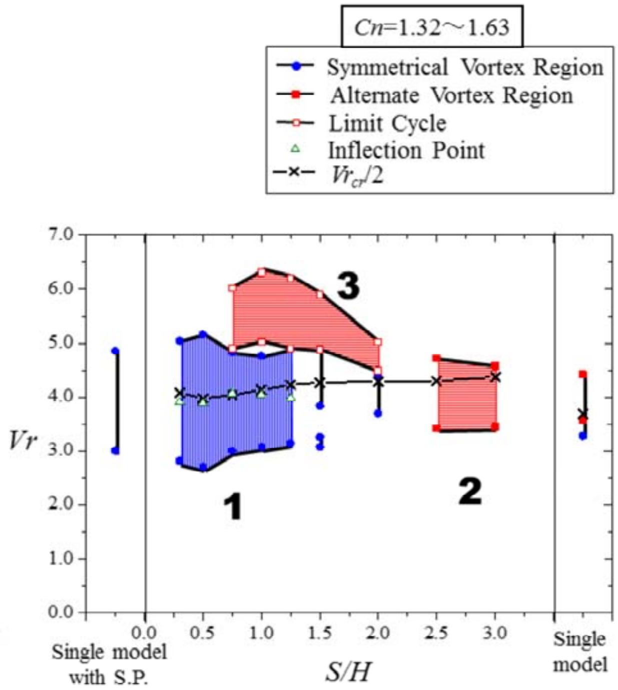


(9) This figure is the results of the upstream cylinder for a gap distance 1. There are separately two excitation regions.The response curve of the first excitation region is very similar to that of the cylinder with a splitter plate. So we show the visualized animations when the upstream cylinder oscillates in this region. A pair of symmetrical vortices form in the gap. And you can find the other excitation, that is called to be an unstable limit-cycle-oscillation. When we give an initial oscillating displacement to the cylinder in this region, the initial oscillation promotes the formation of the alternate vortex shedding, which results in establishing of the so-called unstable limit-cycle oscillation.



(10) This is the results of the streamwise oscillation of the upstream cylinder, when the gap distance becomes relatively wide, that is 2.5. Only one excitation region appears. The visualized animation shows that the upstream cylinder oscillates in the streamwise direction at *Vr* = 4.28, and it is apparent that the alternate Karman vortex-shedding is formed in the gap between the cylinders.

Map of Excitation Regions of Upstream Cylinder as Functions of Gap Distance *s* and Reduced Velocity *Vr*



1. **Movement-induced excitation occurs accompanied by the formation of symmetrical vortices in the gap in front of the downstream cylinder.**
2. **Since the gap distance increases, excitation occurs due to the alternate Karman vortex-shedding.**
3. **The unstable limit cycle oscillation occurs when an initial displacement is given to the cylinder.**

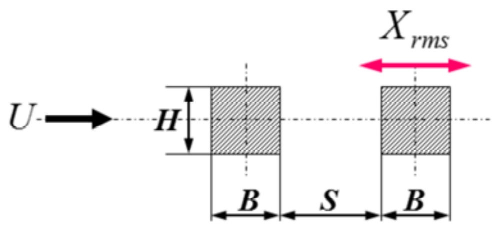
(11) Then we try to make a map of excitation regions of the upstream cylinder as functions of gap distance and reduced velocity. There are three excitation regions.

(1st Region)Movement-induced excitation occurs accompanied by the formation of symmetrical vortices in the gap in front of the downstream cylinder.

(2nd Region) When the gap distance increases, oscillation occurs due to the alternate vortex-shedding.

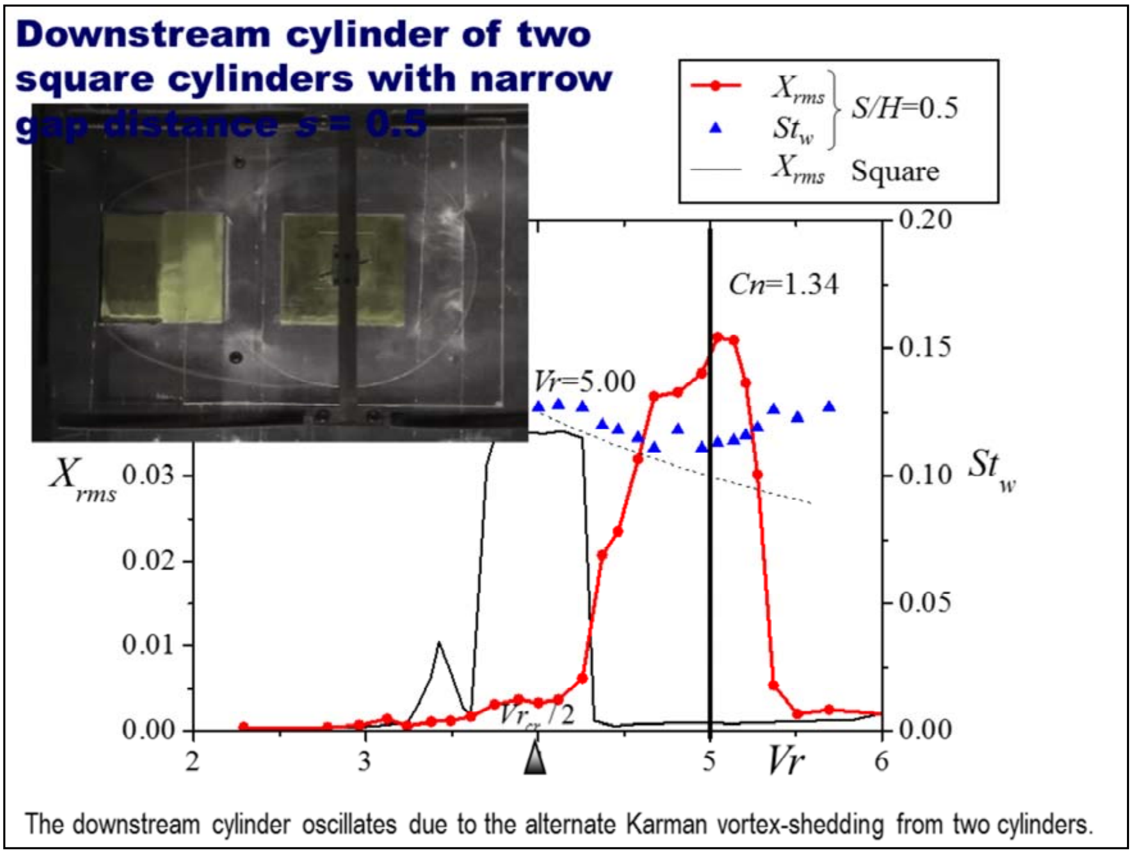
(Last Region) The unstable limit cycle oscillation occurs when an initial displacement is given to the cylinder.

RESULTS : Flow-Induced Streamwise Oscillation of the Downstream Cylinder



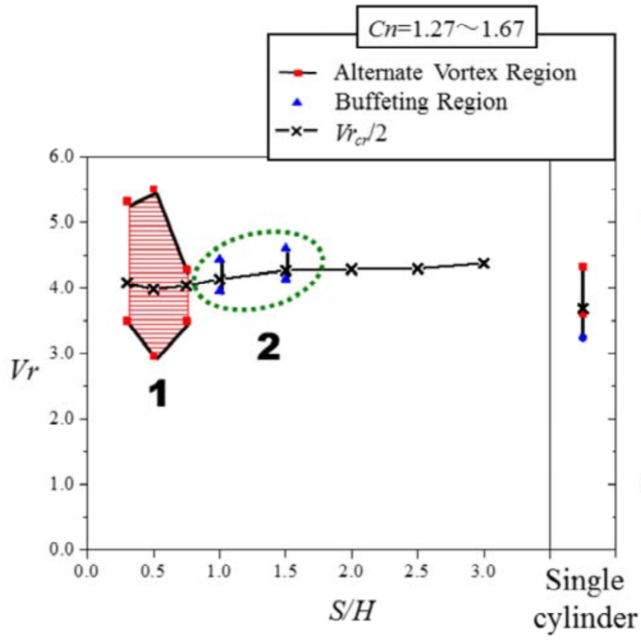
The downstream cylinder is free for streamwise oscillation and the upstream cylinder is fixed.

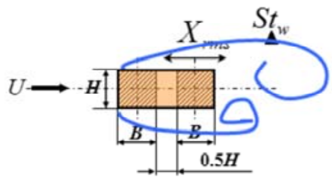
(12) Next we present the results when the downstream cylinder is free for streamwise oscillation and the upstream cylinder is fixed.



(13) We show the response curve of the downstream cylinder for narrow gap distance, *0.5*. You can find only one excitation region is quite different from those of a single cylinder; Then, we show a visualized picture for the downstream cylinder oscillating in the streamwise direction. The downstream cylinder oscillates due to the alternate Karman vortex-shedding from two cylinders.

Map of excitation regions of downstream cylinder as functions of gap distance *s* and reduced velocity *Vr*





1. **The excitation region for the narrow gap distances is induced by the alternate Karman vortex shedding from the two tandem cylinders.**
2. **When *s* is greater than 1, the downstream cylinder experiences buffeting oscillation.**

(14) Finally, we show a map of excitation regions of the downstream cylinder against gap distance and reduced velocity.

(1)The excitation region for the narrow gap distances is induced by the alternate Karman vortex shedding from the two tandem cylinders, connected by the dead water region like this.

(2) When *s* is greater than 1, the downstream cylinder experiences buffeting oscillation.

CONCLUSIONS

1. When the upstream cylinder is free to oscillate, there are two excitation regions: the first region is due to the movement-induced excitation accompanied by the symmetrical vortex shedding, while the second region is due to the vortex excitation by the alternate Karman vortex shedding accompanied with the unstable limit-cycle oscillation.
2. For the range of high velocity, the initial displacement of the up-stream cylinder promotes the periodic reattachment of the separated shear layers of the upstream cylinder to the downstream one, which results in establishing of the unstable limit-cycle oscillation.
3. For wide gaps over 2.5, the excitation region of the upstream cylinder occurs, being due to the alternate Karman vortex shedding, and it resembles the streamwise oscillation of a single cylinder, since the influence of the downstream cylinder becomes small.
4. When the downstream cylinder is free to oscillate for the narrow gap distance, this excitation is apparently induced by the alternate Karman vortex-shedding from the two cylinders
5. When the gap-distance is greater than 1, the downstream cylinder experiences buffeting by wake fluctuation of the upstream cylinder.

(15)Flow-induced in-line oscillation of two tandem circular cylinders was experimentally studied by free-oscillation testing in a wind tunnel. We carried out two kinds of free-oscillation tests of two tandem cylinders.

1. When the upstream cylinder is free to oscillate, there are two excitation regions: the first region is due to the movement-induced excitation accompanied by the symmetrical vortex shedding, while the second is due to the vortex excitation by the alternate Karman vortex shedding accompanied with the unstable limit-cycle oscillation.
2. For the range of high velocity, the initial displacement of the up-stream cylinder promotes the periodic reattachment of the separated shear layers of the upstream cylinder to the downstream one, which results in the unstable limit-cycle oscillation with large amplitude.
3. For wide gaps over 2.5, the excitation region of the upstream cylinder occurs, being due to the alternate Karman vortex shedding, and it resembles the streamwise oscillation of a single cylinder, since the influence of the downstream cylinder becomes small.
4. When the downstream cylinder is free to oscillate for the narrow gap distance, this excitation is apparently induced by the alternate Karman vortex-shedding from the two cylinders connected by the dead water region between them.
5. When the gap-distance is greater than 1, the downstream

cylinder experiences buffeting by wake fluctuation of the upstream cylinder.

REFERENCE

２円柱、直列配置、並列配置、後流中

1. Tanida, Y., Okajima, A., Watanabe, Y.:　Stability of a Circular Cylinder Oscillating in Uniform Flow or in a Wake, Journal of Fluid Mechanics (1973) 61-4, pp.769-784.
2. 渡辺康之、岡島　厚、谷田好通 : 直列におかれた２本の円柱に働く流体力 : 日本機械学会論文集 (1974) 40, 331, pp.765-773.
3. 岡島　厚：高レイノルズ数における直列 2 本円柱まわりの流れ、日本機械学会論文集、(1978) 44, 384, pp.2663-2671
4. 岡島　厚、杉谷賢一郎：直列２本円柱の下流側円柱の静的空力特性、第 7 回風工学シンポジウム論文集、(1982.12) 7, pp.115-122.
5. 岡島　厚、杉谷賢一郎：後流中に置かれた円柱まわりの流れ(静止の時の抵抗とストローハル数) 日本機械学会論文集 B、(1984) 50, 458, pp.2531-2538.
6. 岡島　厚、杉谷賢一郎：高レイノルズ数における並列 2 円柱まわりの流れ、日本機械学会論文集 B、(1986) 52, 480, pp.2844-2850.

複数円柱

7. 岡島　厚、杉谷賢一郎、溝田武人：後流中に置かれた円柱まわりの流れ(自由振動実験)、日本機械学会論文集 B (1986.2) 52, 474, pp.527- 531.
8. Atsushi OKAJIMA, Satoru YASUI, Takahiro KIWATA and Shigeo KIMURA, Flow-induced in-line oscillation of two circular cylinders in tandem arrangement, Proceedings of PVP2006-ICPVT-11, 2006 ASME Pressure Vessels and Piping Division Conference PVP2006-ICPVT11-93873, Vancouver, BC, Canada, (2006.7)
9. Atsushi OKAJIMA, Satoru YASUI, Takahiro KIWATA, Shigeo KIMURA：FLOW-INDUCED STREAMWISE OSCILLATION OF TWO CIRCULAR CYLINDERS IN TANDEM ARRANGEMENT, Conference on Modelling Fluid Flow (CMFF’06), The 13th International Conference on Fluid Flow Technologies, Budapest, Hungary, (2006.9)
10. 岡島　厚，安井　聡，木村繁男，木綿隆弘：直列２円柱の流れ方向流力振動に関する研究、日本機械学会論文集 B, (2007.2), 73-726, pp.428-436.
11. Atsushi OKAJIMA, Satoru YASUI, Takahiro KIWATA, Shigeo KIMURA, Flow-Induced Streamwise Oscillation of Two Circular Cylinders in Tandem Arrangement, International Journal of Heat and Fluid Flow 28 (2007) pp.552-560.
12. Atsushi OKAJIMA, Takahiro KIWATA, Satoru YASUI, Yoshiki MORI and Shigeo KIMURA, Flow-induced streamwise oscillation of two square cylinders in tandem arrangement, Proceedings of PVP2007/CREEP8,
13. 2007 ASME Pressure Vessels and Piping Division Conference PVP2007, PVP2007-26123, San Antonio, Texas, USA, July 22-26, 2007.7.

複数静止矩形構造物の静特性

14. 岡島　厚、木綿隆弘：直列配置の２矩形柱の空力静特性、構造工学論文集、(1990.3) 36A, pp.849-857.
15. 岡島　厚、上野久儀、木綿隆弘、恵上浩一：並列角柱の空力静特性におよぼす迎え角の影響、構造工学論文集、(1992.3) 38A, pp.857- 864.

複数矩形柱

16. 岡島　厚、阿部彰人、木綿隆弘：直列２矩形柱の空力不安定振動、構造工学論文集、(1990.3) 36A, pp.859- 864.
17. 岡島　厚，安井　聡，森　快貴，木村繁男，木綿隆弘：直列２角柱の流れ方向流力振動に関する研究、日本機械学会論文集 B (2007.1), 73-725, pp.76-84
18. Takahiro KIWATA, Atsushi OKAJIMA, Flow-induced streamwise oscillation of two square cylinders in tandem arrangement, 9th International Conference on Flow-Induced Vibration - FIV2008, (2008-7) Prague, Czech Republic.

種々な断面柱

19. Okajima, A., Ueno, H., Yi, D.: Study on Aerostatic Characteristics and Aeroelastic Instability of Structural L-Shaped, T-Shaped and Cross-Shaped Sections, Proceedings of Third ASIA-PACIFIC Symposium Wind Eng., (1993.12) pp.649-654.
20. Okajima, A., Ueno, H., Yi, D.: Observations of Flows about a Longitudinally Oscillating Cylinder with Rectangular Cross-Sections, Proceedings of 3rd Asian Symposium on Visualization, (1994.5) A16, pp.46- 50.
21. 岡島　厚、上野久儀、阿部彰人：隅切り矩形断面柱の空力特性におよぼすレイノルズ数の影響、日本風工学会誌、(1991.11) 49, pp.1- 13.
22. Mizota, T., Okajima, A.: Unsteady Aerodynamic Forces and Wakes of Rectangular Prisms with Oscillating Flaps at Leading Edges, Journal of Wind Engineering and Industrial Aero., (1992.10) 41, 44, pp.727- 738

REFERENCES

２円柱、直列配置、並列配置、後流中

1. Tanida, Y., Okajima, A., Watanabe, Y.: Stability of a Circular Cylinder Oscillating in Uniform Flow or in a Wake, Journal of Fluid Mechanics (1973) 61-4, pp.769-784.
2. 渡辺康之、岡島　厚、谷田好通：直列におかれた２本の円柱に働く流体力：日本機械学会論文集 (1974) 40, 331, pp.765-773.
3. 岡島　厚：高レイノルズ数における直列２本円柱まわりの流れ、日本機械学会論文集、(1978) 44, 384, pp.2663-2671
4. 岡島　厚、杉谷賢一郎：直列２本円柱の下流側円柱の静的空力特性、第７回風工学シンポジウム論文集、(1982.12) 7, pp.115-122.
5. 岡島　厚、杉谷賢一郎：後流中に置かれた円柱まわりの流れ(静止の時の抵抗とストローハル数) 日本機械学会論文集 B、(1984) 50, 458, pp.2531-2538.
6. 岡島　厚、杉谷賢一郎：高レイノルズ数における並列２円柱まわりの流れ、日本機械学会論文集 B、(1986) 52, 480, pp.2844-2850.

複数円柱

7. 岡島　厚、杉谷賢一郎、溝田武人：後流中に置かれた円柱まわりの流れ(自由振動実験)、日本機械学会論文集 B (1986.2) 52, 474, pp.527- 531.
8. Atsushi OKAJIMA, Satoru YASUI, Takahiro KIWATA and Shigeo KIMURA, Flow-induced in-line oscillation of two circular cylinders in tandem arrangement, Proceedings of PVP2006-ICPVT-11, 2006 ASME Pressure Vessels and Piping Division Conference PVP2006-ICPVT11-93873, Vancouver, BC, Canada, (2006.7)
9. Atsushi OKAJIMA, Satoru YASUI, Takahiro KIWATA, Shigeo KIMURA：FLOW-INDUCED STREAMWISE OSCILLATION OF TWO CIRCULAR CYLINDERS IN TANDEM ARRANGEMENT, Conference on Modelling Fluid Flow (CMFF’06), The 13th International Conference on Fluid Flow Technologies, Budapest, Hungary, (2006.9)
10. 岡島　厚，安井　聡，木村繁男，木綿隆弘：直列２円柱の流れ方向流力振動に関する研究、日本機械学会論文集 B, (2007.2), 73-726, pp.428-436.
11. Atsushi OKAJIMA, Satoru YASUI, Takahiro KIWATA, Shigeo KIMURA, Flow-Induced Streamwise Oscillation of Two Circular Cylinders in Tandem Arrangement, International Journal of Heat and Fluid Flow 28 (2007) pp.552-560.
12. Atsushi OKAJIMA, Takahiro KIWATA, Satoru YASUI, Yoshiki MORI and Shigeo KIMURA, Flow-induced streamwise oscillation of two square cylinders in tandem arrangement, Proceedings of PVP2007/CREEP8,
13. 2007 ASME Pressure Vessels and Piping Division Conference PVP2007, PVP2007-26123, San Antonio, Texas, USA, July 22-26, 2007.7.

複数静止矩形構造物の静特性

14. 岡島　厚、木綿隆弘：直列配置の２矩形柱の空力静特性、構造工学論文集、(1990.3) 36A, pp.849-857.
15. 岡島　厚、上野久儀、木綿隆弘、恵上浩一：並列角柱の空力静特性におよぼす迎え角の影響、構造工学論文集、(1992.3) 38A, pp.857- 864.

複数矩形柱

16. 岡島　厚、阿部彰人、木綿隆弘：直列２矩形柱の空力不安定振動、構造工学論文集、(1990.3) 36A, pp.859- 864.
17. 岡島　厚，安井　聡，森　快貴，木村繁男，木綿隆弘：直列２角柱の流れ方向流力振動に関する研究、日本機械学会論文集 B (2007.1), 73-725, pp.76-84
18. Takahiro KIWATA, Atsushi OKAJIMA, Flow-induced streamwise oscillation of two square cylinders in tandem arrangement, 9th International Conference on Flow-Induced Vibration - FIV2008, (2008-7) Prague, Czech Republic.

種々な断面柱

19. Okajima, A., Ueno, H., Yi, D.: Study on Aerostatic Characteristics and Aeroelastic Instability of Structural L-Shaped, T-Shaped and Cross-Shaped Sections, Proceedings of Third ASIA-PACIFIC Symposium Wind Eng., (1993.12) pp.649-654.
20. Okajima, A., Ueno, H., Yi, D.: Observations of Flows about a Longitudinally Oscillating Cylinder with Rectangular Cross-Sections, Proceedings of 3rd Asian Symposium on Visualization, (1994.5) A16, pp.46- 50.
21. 岡島　厚、上野久儀、阿部彰人：隅切り矩形断面柱の空力特性におよぼすレイノルズ数の影響、日本風工学会誌、(1991.11) 49, pp.1- 13.
22. Mizota, T., Okajima, A.: Unsteady Aerodynamic Forces and Wakes of Rectangular Prisms with Oscillating Flaps at Leading Edges, Journal of Wind Engineering and Industrial Aero., (1992.10) 41, 44, pp.727- 738