Lower Mode Response of Circular Cylinders in Cross-Flow

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Transverse amplitude responses of a circular cylinder in cross-flow were determined as a function of reduced velocities for a variety of spring constants and damping coefficients. Maxima were found at reduced velocities of 5 and 16, and were of comparable amplitude. The first resonance, designated the "fundamental mode," was due to normal vortex street excitation of the spring-mass system. The second resonance, designated the "lower mode," occurred when the natural frequency was approximately one-third of the normal vortex shedding frequency. By assuming that the driving force was sinusoidal, it was possible to evaluate the lift coefficients at resonance. Lift coefficients for the lower mode behaved similarly with amplitude ratio but were an order of magnitude lower than lift coefficients for the fundamental mode. A mechanism was used to oscillate the cylinder transversely at prescribed frequencies and amplitudes. Dominant wake frequencies were determined from a frequency analysis of the hot-wire signal for a range of velocities and a fixed frequency of oscillation. It was found that synchronization of the shedding frequency to the forcing frequency did not take place for the lower mode. The familiar "lock-in" region, or frequency synchronization over finite bandwidth, was observed for the fundamental mode only. Since the frequency associated with normal vortex shedding was not suppressed when oscillations took place in the lower mode, it would seem that a low frequency vortex street had not replaced the normal one. It is likely, then, that the spring-mounted cylinder responded subharmonically to the exciting force resulting from vortex shedding. In this regard, however, it was curious that subharmonic response was not found at a frequency ratio of 0.5 as it was at 0.33. A conceptual model, which incorporated features of both the low frequency vortex street and subharmonic response, was developed which accounted for lower mode response at a frequency ratio of 0.33 as well as the lack of response at 0.5.

Introduction

Circular cylinders exposed to cross-flow are known to experience aerodynamic excitation as a consequence of the trailing vortex street. When the shedding frequency is near the natural frequency of the mechanical system, lock-in to the latter takes place and vibrations of substantial amplitude can occur if damping is relatively small. For Reynolds numbers above 300, the phenomenon is characterized by a Strouhal number $S = f_s d/U \approx 0.2$, where the shedding frequency is nearly equal to the natural frequency $f_s \approx f_n$.

The recent review by King [1] provides a good introduction to the subject of oscillations induced by vortex shedding. Papers by Bishop and Hassan [2], Koopmann [3], Toebes and Ramamurthy [4], Jones [5], and Blevins [6], provide more detailed results, especially with regard to the synchronization of vortex shedding with lateral vibrations of circular cylinders. One notable feature of this phenomenon is that the force

is directly related to the vortices which are shed alternately from each side of the cylinder with each pair of opposite signs causing one full force cycle. Another is that the ensuing cylinder oscillation substantially affects the vortex shedding process. Near resonance in the fundamental mode (designating phenomena taking place near $S = 0.2$), the shedding becomes highly organized, longitudinally, and the shedding frequency is entrained to the natural frequency of the spring-mass system. Mathematical models, incorporating essential features of the fluid and mechanical systems, have not been put forth by Hartlen and Currie [7], Skop and Griffin [8], and Iwan and Blevins [9].

Of particular relevance to the present investigation is the possibility of resonance in modes other than the fundamental mode. Various definitions of frequencies associated with the processes involved are defined as follows:

f_s = vortex shedding frequency
f_{so} = vortex shedding frequency for rigidly supported cylinder
f_n = natural frequency of mechanical system
f_f = frequency of mechanically forced cylinder motion

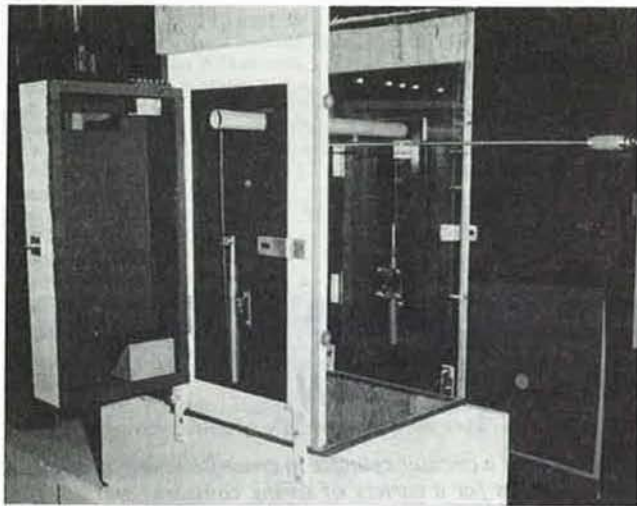For the present purposes, the modes are defined as:
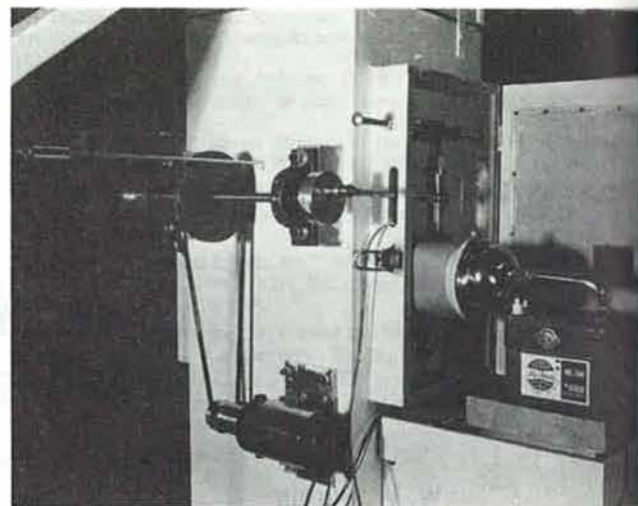

Fig. 1 Elastically mounted cylinder

Fig. 2 Mechanically oscillated cylinder

Higher mode	$f_n > f_{so}$
Fundamental mode	$f_n = f_s = f_{so} (1 \pm \epsilon)$
Lower mode	$f_n < f_{so}$

where ϵ is small and is indicative of the synchronization bandwidth during fundamental mode lock-in. Bishop and Hassan [2] found response in the higher mode (frequency demultiplication, in their terminology) for mechanically oscillated cylinders. Time records of the force in linkage between the oscillation mechanism and the cylinder showed frequency components at $f_f/2$ and $f_f/3$ when the forcing frequency was approximately 2 and 3 times the shedding frequency, respectively. Although this conclusion seems clear from their representative force traces, quantitative evaluation using force measurements of this sort are difficult because of the large inertial contribution to the record.

Toebes [10], by examining hot-wire records of wake velocities behind cylinders undergoing mechanically forced oscillations, also found higher mode response at ratios of 2 and 3. Additionally, he observed lower mode response at a ratio of 0.5; that is, the vortex shedding frequency, f_{so}, was approximately twice the cylinder oscillation frequency.

Penzien [11] obtained records of strain from cantilever beams supporting cylinders which could vibrate laterally. While it is not possible to infer amplitude of motion from his published data, lower mode response can be observed for some test cases. The frequency ratio was, at times, near 0.33 although the results are not consistent. In addition, the lower mode response was occasionally larger than the fundamental response.

Lienhard and Liu [12] investigated the frequency of vortex shedding behind a mechanically oscillated cylinder and found indications of lock-in for both higher and lower modes as well as for the fundamental mode. Except for the fundamental mode, the locked-in regions were not distinct. One test series

indicated lower mode response at a ratio of 0.55, while several showed the higher mode.

Quite by accident, Gowing [13], while investigating the possibility of using lock-in at the fundamental mode as a means of extracting work from a flowing fluid, discovered that his spring-mounted cylinder was vibrating with large amplitude at a frequency much lower than predicted for normal vortex shedding. The cylinder was mounted on a long, flexible leaf spring at its center and facing upstream in a wind tunnel. The apparatus was designed to produce large amplitude oscillation to facilitate the use of a simple electric generator. It was found that substantially greater oscillation could be maintained in the lower mode than in the fundamental mode, resulting in greater power extraction.

It was hypothesized that a vortex street of low frequency was either shed directly or formed quickly through coalescence. The latter has been demonstrated experimentally for evolving streets by Taneda [14], and Durgin and Karlsson [15] for single cylinders, while Thomas and Kraus [16] and Zdravkovich [17] made similar findings for multiple cylinder arrangements. Numerical studies by Acton [18] and Christiansen and Zabusky [19] have also exhibited coalescence. Additionally, Griffin and Votaw [20] examined the wakes of laterally vibrated cylinders using smoke visualization demonstrating vortex elongation which precedes vortex fission, although fission was not observed.

Alternatively, the observed response could have been caused by sub-harmonic response of the spring-cylinder system to excitation by the usual vortex street. Two different types of experiments were conducted to help clarify the nature of the observed lower mode response. In the first series of experiments, Stasaitis [21] utilized cylinders which were elastically supported in a manner similar to Gowing's [13]. The apparatus was used to document the phenomenon and explore the effect of various parameters. In the second series

─────── Nomenclature ───────

a = amplitude of cylinder motion
C_l = lift coefficient
d = cylinder diameter
f = frequency
f_s = vortex shedding frequency
f_{so} = frequency based on $S = 0.2$
f_n = natural frequency
f_f = frequency of mechanically

forced cylinder motion
M = equivalent mass per unit length
P_f = spectral density as percent of area under spectrum
P_{fn} = spectral density at f_n
P_{fs} = spectral density at f_s
R = Reynolds number = Ud/ν
S = Strouhal number = fd/U
t = time

U = free stream velocity
U_r = reduced velocity = $U/f_n d$
x = streamwise coordinate
y = lateral coordinate
δ_r = reduced damping
δ_s = logarithmic decrement of damping
ν = kinematic viscosity of fluid
ρ = fluid density
τ = time constant

Test No.	f_n (HZ)	U (m/sec)	τ (sec)	M (gm/cm)	δ_s	δ_r	R	U/fd	a/d	C_ℓ
1	8.4	3.41	7.9	0.303	0.0151	1.27	5690	16.4	0.230	0.014
2	9.0	3.50	7.6	0.302	0.0147	1.23	5790	15.6	0.184	0.011
3	9.5	3.75	6.8	0.301	0.0154	1.28	6250	15.9	0.196	0.012
4	10.0	3.78	5.6	0.301	0.0179	1.49	6300	15.2	0.191	0.014
5	10.7	4.15	5.4	0.299	0.0172	1.42	6860	15.6	0.159	0.013
6	11.5	4.51	5.2	0.298	0.0167	1.38	7520	15.9	0.180	0.012
7	13.6	5.36	4.8	0.295	0.0154	1.26	8940	15.9	0.145	0.009
8	16.5	6.16	3.2	0.292	0.0191	1.55	10260	15.2	0.129	0.010
9	19.4	7.38	1.2	0.291	0.0433	3.48	12300	15.4	0.103	0.017
10	8.1	3.05	8.2	0.304	0.0150	1.26	5080	15.2	0.159	0.010
11	7.7	3.23	8.4	0.285	0.0155	1.22	5390	17.0	0.134	0.008
12	6.7	2.74	9.6	0.288	0.0155	1.23	4570	16.4	0.123	0.008
13	5.7	2.07	10.9	0.291	0.0161	1.30	3460	14.7	0.097	0.006
18	15.5	6.43	3.2	0.281	0.0204	1.78	10720	16.7	0.104	0.009
19	12.2	4.88	5.0	0.285	0.0164	1.45	8130	16.1	0.212	0.015
20	10.1	4.27	5.4	0.288	0.0183	1.64	7110	17.0	0.155	0.012
21	8.1	3.26	7.4	0.292	0.0166	1.50	5440	16.1	0.165	0.012
22	11.5	4.79	5.6	0.280	0.0156	1.21	7980	16.7	0.214	0.013
23	8.2	3.54	8.2	0.285	0.0149	1.17	5890	17.5	0.212	0.012
24	6.1	2.53	10.2	0.290	0.0161	1.29	4220	16.7	0.120	0.008
Error	±0.5%	±0.5%	±1%	±0.5%	±1.5%	±2.8%	±0.9%	±1.4%	±3.4%	±9%

of experiments, Lefebvre [22] used a cylinder which was mechanically oscillated and observed the response of the wake in the range of interest.

Experimental Apparatus

This investigation utilized a vertical wind tunnel with a test section measuring 30 cm by 30 cm. The vertical orientation eliminated static deflection of the cylinders, which were mounted on flexible springs, Fig. 1. Air entered the tunnel through a rounded entrance and proceeded through the test section, a vaned elbow, blower, Venturi meter, and regulating valve. For the first series of experiments, rigid paper and plastic composite cylinders were attached to leaf springs mounted in telescoping clamps on the outside of the tunnel wall. The cylinders passed through slots in the walls so that approximately 3 cm on each end were not in the air stream. The slots and telescoping clamps were sealed from the room environment by hinged, air tight boxes. Both cantilever springs vibrated in unison in the fundamental mechanical mode. The frequency of the second mechanical mode was about 30 times the fundamental. Except for the side wall boundary layers, the flow in the test section was uniform within the resolution of the hot-wire. The turbulence intensity varied from 1.7 percent at the highest speed to 6.0 percent at the lowest speed.

To monitor cylinder oscillations, a photo cell was coupled to an amplifier and used to monitor the intensity of light modulated by a shield connected to the spring-cylinder combination. A digital counter was used to determine the frequency of oscillation, and the amplitude of oscillation was taken directly from a storage oscilloscope.

For the second series of experiments, the cylinder was mounted on a mechanism capable of imparting harmonic motion, as shown in Fig. 2. A crankshaft with adjustable stroke was driven through a rubber belt by a stepping motor with feedback speed control. The photo cell arrangement was again used to monitor cylinder motion.

Observation of wake velocities was made for both experimental series using a commercial hot-wire anemometer. For the experiments with forced cylinder oscillation, spectral analysis was performed by tape recording and digitally analyzing the signal on a computer system.

Results

Both measured and derived parameters for peak lower mode response of elastically mounted cylinders are listed in Table 1. Figure 3 shows the non-dimensional cylinder motion amplitude, a/d, versus the reduced velocity, $U_r = U/f_n d$ for six different natural frequencies, f_n. The fundamental mode response to vortex shedding is visible as the peaks near $U_r = 5$

(Strouhal number S = 0.2). The peak responses are generally somewhat smaller than those obtained by other investigators. The low values of damping and the treatment of the sidewalls probably contribute to this difference. In addition, the peak values are not entirely consistent with the reduced damping values. The reason for this behavior is not presently understood. Additional peaks are apparent near $U_r = 16$ and reflect substantial oscillatory response to the flowing stream. The reduced velocity at the secondary peak was essentially independent of Reynolds number over the range tested, as can be seen from Fig. 4. Values of the reduced damping, δ_r, were rather small because of the small cylinder mass.

Evidently, in the lower mode, the spring mounted cylinder experienced an exciting force at approximately one-third the normal vortex shedding frequency associated with the flow velocity. By assuming the exciting force to be sinusoidal, the lift coefficient for lower mode resonance could be evaluated. Blevins and Burton (23), for example, give the equation

$$C_l = \delta_r \frac{a}{d} \frac{(2\pi S)^2}{\pi} \qquad (1)$$

where δ_r is the reduced damping

$$\delta_r = \frac{2M\delta_s}{\rho d^2} \qquad (2)$$

The logarithmic decrement of damping, δ_s, was evaluated from vibration decay curves with no air flow, as indicated in Blevins [24]. These values were measured for only a single perturbation from equilibrium so that amplitude dependence was not investigated. The curves, however, appeared exponential. The mass per unit length, M, includes the cylinder mass, hydrodynamic mass, and a portion of the spring mass. Here, the Strouhal number is evaluated as the reciprocal of the reduced velocity, U_r. Figure 5 shows that the lift coefficient increased with amplitude over the experimental range in a manner comparable to that of the fundamental mode. The magnitudes, however, are an order of magnitude less than those associated with typical fundamental mode response.

In the second series of experiments, the 2.48 cm diameter cylinder was oscillated with an amplitude of $a/d = 0.175$ at a frequency of 10.1 Hz. The hot-wire probe was positioned at $x/d = 3.0$ and $y/d = 1.3$. Velocities at this location were found to provide relatively large power spectral density for both the forcing frequency and vortex shedding frequency over the range of velocities used. Signal analyses were performed such that the frequency range 0-51 Hz was spanned with a resolution of 0.1 Hz. A low pass filter with a roll-off of 18 db/octave set at 50 Hz was provided at the input of the A/D converter to eliminate foldover. The output spectra were normalized individually so that the highest peak always
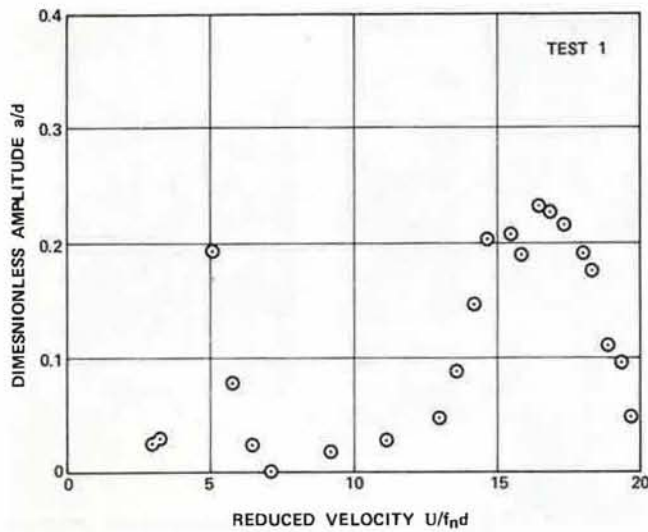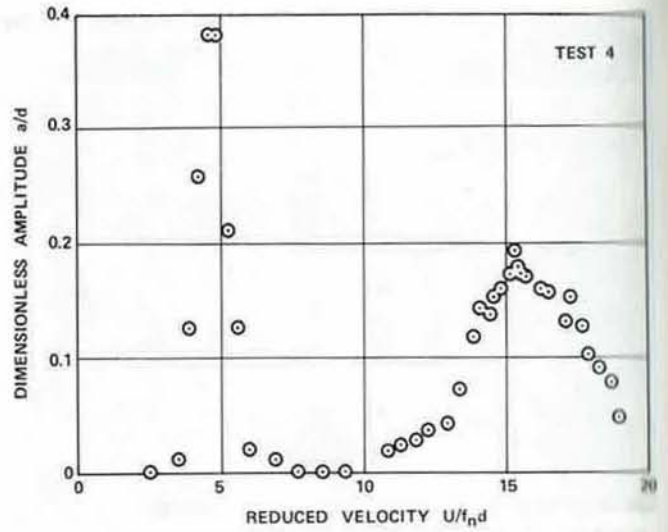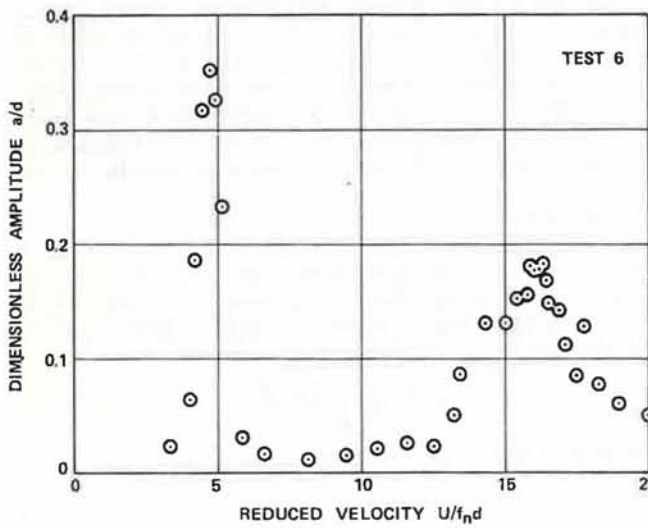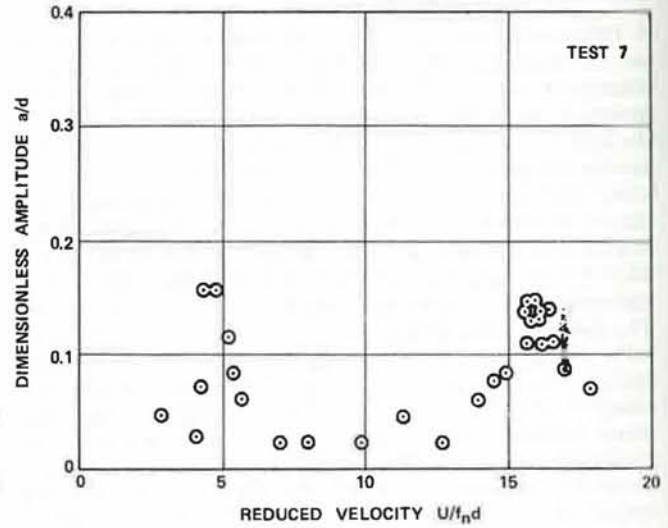
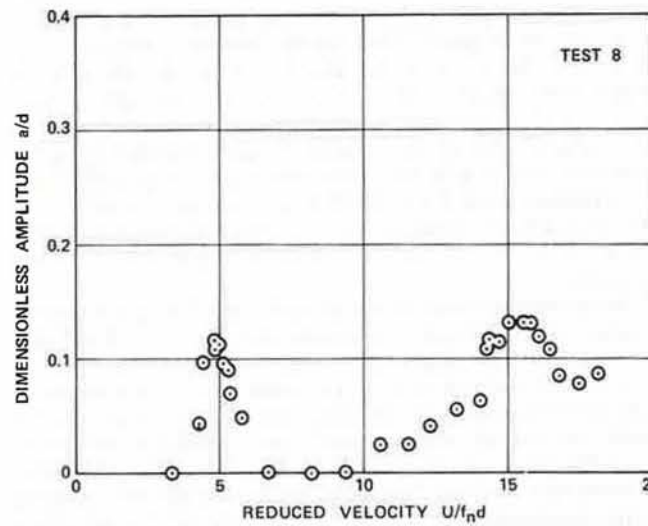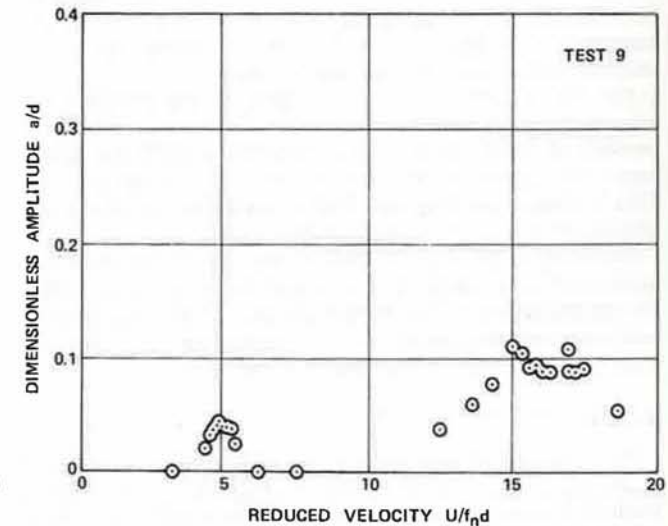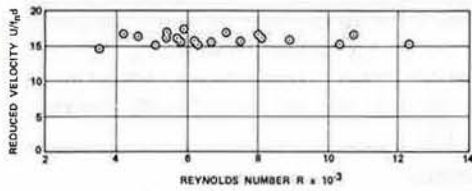Fig. 3 Amplitude response of elastically mounted cylinders

Fig. 4 Reduced velocity of lower mode response versus Reynolds number

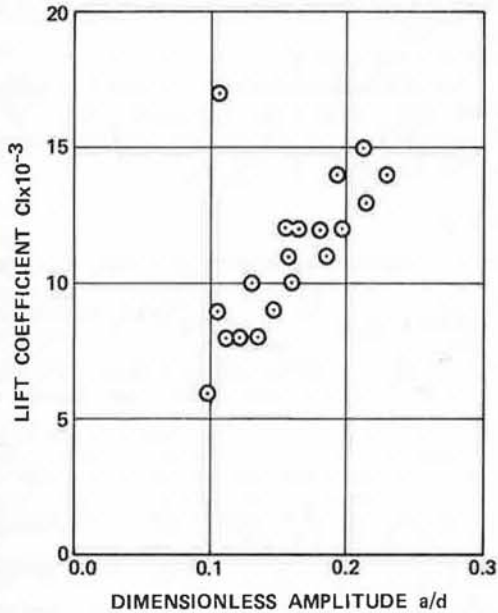Fig. 5 Lower mode lift coefficient variation with amplitude

R	f_f/f_{so}	P_{fso} (%)	P_{ff} (%)
1580	1.64	4.14	1.76
2370	1.00	32.16	32.16
4480	0.53	1.97	3.92
4740	0.50	2.09	2.14
6460	0.36	2.92	1.38
7120	0.33	1.41	0.77
Error	$\pm 0.9\%$	$\pm 1.0\%$	$\pm 0.5\%$	$\pm 0.5\%$
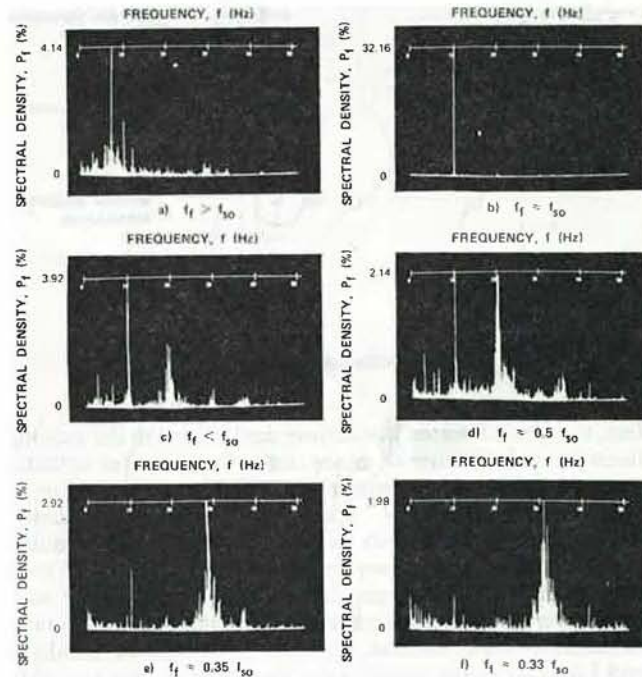
Fig. 6 Power spectra for various frequency ratios
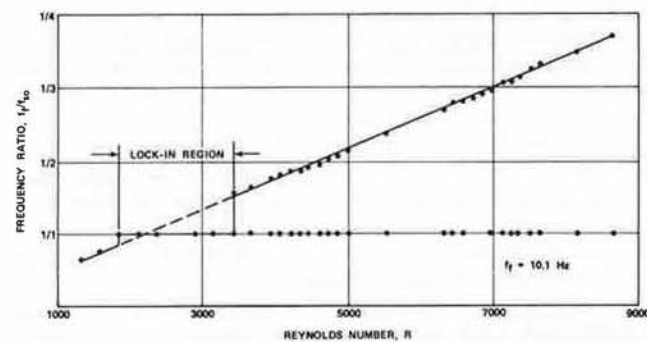
Fig. 7 Wake response for various free stream velocities

equalled full scale on the graphics screen. The value of the highest peak relative to the integral under the spectrum, P_f, was calculated as percent and is tabulated in Table 2 as either P_{so} or P_{ff} as appropriate. The Reynolds number, R, and the frequency ratio, f_f/f_{so}, are also tabulated.

Figure 6 shows power spectra for various air velocities. In (a), the shedding frequency is less than the forcing frequency, and distinct peaks can be seen for each. Synchronization has been achieved in (b), and all energy is at 10.1 Hz. In (c), synchronization has been lost and the forcing frequency is less than the shedding frequency. For $f_f/f_{so} = 0.5$, (d), substantial energy can be found at both frequencies. In (e), the conditions of the freely vibrating cylinder are approached, and the energy at the forcing frequency is considerably less than at the shedding frequency. For conditions approximately the same as those for the freely vibrating case, (f), the energy at the forcing frequency is even smaller.

A total of 33 spectra were obtained for Reynolds numbers between 1318 and 8697. The results are summarized in Figure 7, where lock-in in the fundamental mode can be clearly seen. At frequency ratios $f_f/f_{so} = 0.5$ and 0.33, distinct lock-in was not achieved. Both frequencies were, however, clearly present above the fundamental mode lock-in region.

An error analysis based on direct propagation of estimated measurement inaccuracies was made. Maximum errors, in percents to be associated with derived quantities, are tabulated at the end of Tables 1 and 2.

Discussion

The spring mounted cylinder experienced excitation at $f_n/f_{so} = 0.33$. Although the lift coefficients were relatively small, the cylinders, nevertheless, experienced substantial vibration amplitude. This response probably resulted from the low reduced damping used, which would explain why no other investigators have distinctly observed the phenomena. If the free oscillation and forced oscillation situations are fluid mechanically equivalent, then, under the hypothesis that a low frequency vortex street was formed, the shedding frequency should have been entrained to the forced oscillation frequency near $f_f/f_{so} = 0.33$. This was not found to be true and, in fact, most of the energy associated with fluctuating wake velocities was found at f_{so}.

The lower mode response could have been subharmonic excitation by the (higher) vortex shedding frequency. In ef-
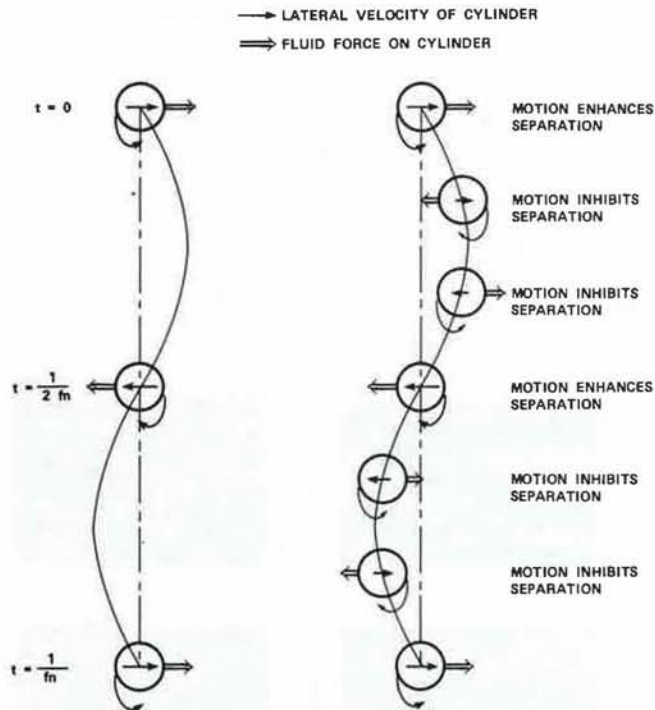
→ LATERAL VELOCITY OF CYLINDER
⟹ FLUID FORCE ON CYLINDER

t = 0   MOTION ENHANCES SEPARATION

MOTION INHIBITS SEPARATION

MOTION INHIBITS SEPARATION

$t = \frac{1}{2\,f_n}$ MOTION ENHANCES SEPARATION

MOTION INHIBITS SEPARATION

MOTION INHIBITS SEPARATION

$t = \frac{1}{f_n}$

Fig. 8   Vortex shedding at $f_n \approx f_{so}$ and $f_n \approx f_{so}/3$

fect, every third vortex would have contributed to the exciting force for half of a cycle. Since the spring-mounted cylinder vibrated in two modes with an effective frequency ratio of approximately $5/16 = 0.31$ (0.29 average by actual calculation for each test) rather than 0.33, the Strouhal number would have to have decreased from 0.21 to 0.19 over the Reynolds number range 1000 to 8000. This behavior was, in fact, verified using spectral analysis of the wake of a rigidly mounted cylinder. Similar behavior was found by Lienhard and Liu [12]. In the present case, the variation was probably due to the sidewall treatment and its effect on base pressure as well as the free stream turbulence variation with tunnel speed. More peculiarly, the spring-mounted cylinder did not respond at a frequency ratio $f_f/f_{so} = 0.50$ as found by Toebes [10] and Linenhard and Liu [12]. Effectively for this mode, every other shed vortex of the same sign would contribute to the exciting force for half of a cycle. The spectral analysis, however, for the cylinder undergoing forced oscillation near $f_f/f_{so} = 0.50$ indicated conditions similar to $f_f/f_{so} = 0.33$. So, explanation in terms of subharmonic response cannot be altogether consistent either.

A vortex shedding sequence which encompasses aspects of both the low frequency vortex street hypothesis and the subharmonic response hypothesis is depicted in Fig. 8. During fundamental mode response, which is shown for comparison, vortex shedding is enhanced by motion of the cylinder. The lateral velocity promotes separation causing a vortex to form. The resulting force thus bears the proper relationship to the velocity.

Basically, the same sequence can occur with two intervening vortices added. The extra vortices are located at positions in the cycle such that separation is inhibited, thus resulting in weaker vortices. The ensuing forces do not act in the direction of motion and thus tend to retard motion. However, under conditions of small damping, as in the present study, sufficient energy is put into each half-cycle by every third vortex to overcome damping and the retarding force of the intervening vortices. Velocity fluctuations in the wake would exhibit frequencies of f_{so} and $f_{so}/3$. It would seem that there is no possible arrangement which can result in a similar

sequence at $f_{so}/2$. In this case, of course, equation (1) cannot estimate the lift coefficients. Ericsson [25] has extended this method of description to explain other lateral modes as well as in-line modes experimentally observed by Wootten, et al. [26] and King [1].

Conclusions

Lower mode response of elastically mounted cylinders near $f_n = f_{so}/3$ can occur providing damping is small. Synchronization over finite bandwidth (lock-in) was not observed, however.

Similar response was not found for $f_n = f_{so}/2$.

A conceptual model which combines some features of a low frequency vortex street with subharmonic response can be used to explain lower mode response and the difference in observed behavior at $f_{so}/2$ and $f_{so}/3$.

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—————— DISCUSSION ——————

L. E. Ericsson.[3] The interesting results obtained by Durgin, et al. [27], for subharmonic response to Karman vortex shedding on a cylinder in crossflow are very much in agreement with the findings in a recently completed analysis of vortex-induced asymmetric loads [28]. In Fig. 1 the case $f = f_{v0}/2$ has been added to Fig. 8 of reference [27], to illustrate the effect of the translatory deflection. The situation in Fig. 1 is analogous to that existing for a pitching airfoil [29]. The moving wall has a wall-jet-like effect on the boundary layer development between stagnation and separation points. The downstream moving wall delays separation and causes a large overshoot of static lift maximum on a pitching airfoil [29]. The upstream moving wall effect is to promote separation. This adverse effect is even more powerful than the beneficial effect of the downstream moving wall, as is demonstrated by Swanson's results for a rotating cylinder [30]. Returning to Fig. 1 it can be seen that for $f = f_{v0}$ at each vortex shedding event, alternating between top and bottom sides of the cylinder, the upstream moving wall effect promotes separation, thus enhancing the vortex-induced transverse force and causing the observed strong translatory response of the cylinder to the Karman vortex shedding [27]. At $f = f_{v0}/2$, however, the translatory velocity-moving wall effect is zero for the vortex shedding events taking place at maximum deflection. And at zero deflection, where the moving wall effect is maximum, it alternates between enhancing and opposing the vortex shedding, explaining why no cylinder response to the vortex shedding was observed at this frequency [27]. Finally, for $f = f_{v0}/3$, the maximum moving wall effect obtained at zero

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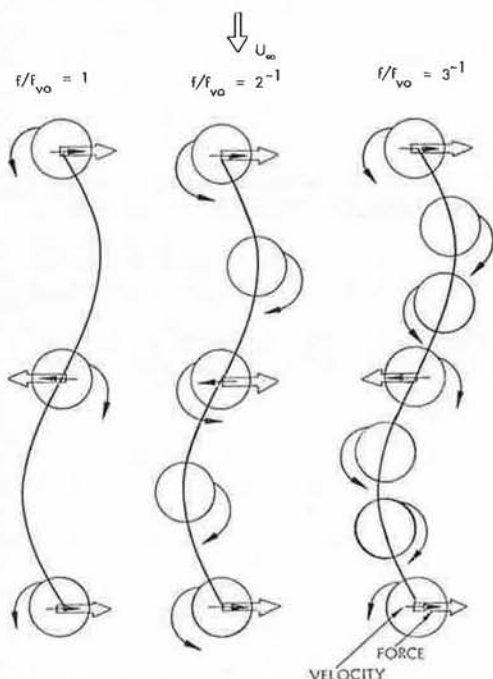[3] Lockheed Missiles and Space Co., Inc., Sunnyvale, Claif.

Fig. 1 Vortex shedding from translating cylinder at $f = f_{v0}$, $f = f_{v0}/2$ and $F = f_{v0}/3$
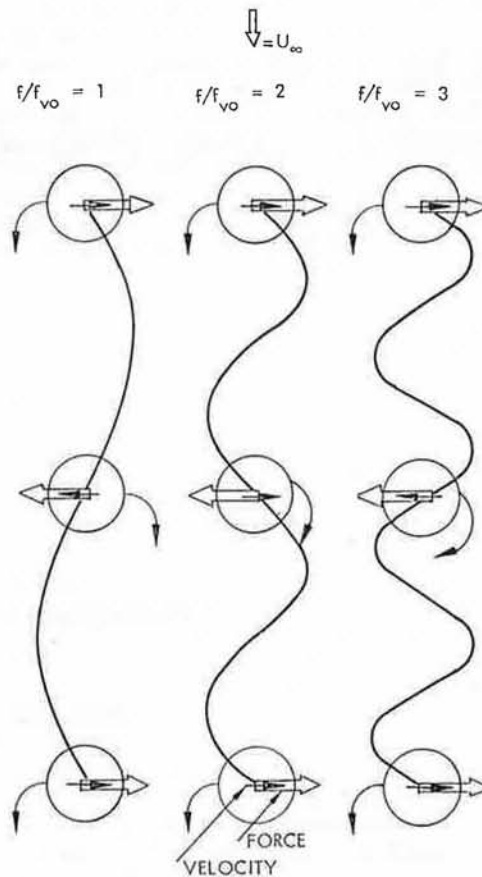

Fig. 2 Vortex shedding from translating cylinder at $f = f_{v0}$, $f = 2 f_{v0}$ and $f = 3 f_{v0}$
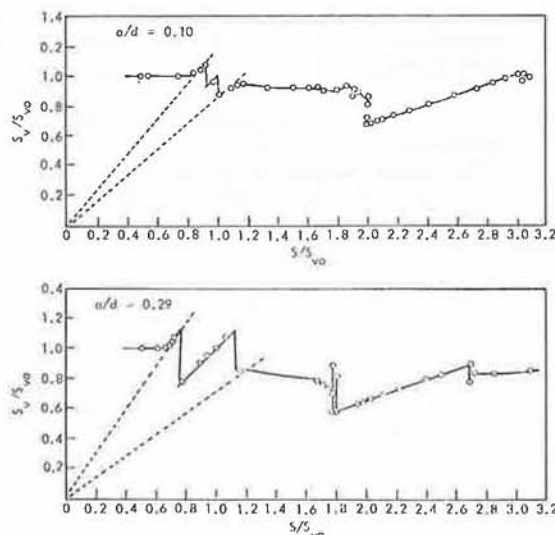

Fig. 3 Effect of translatory oscillation on cylinder vortex shedding

deflection always enhances the vortex shedding, as in the case of $f=f_{v0}$. For the intermediate pair of vortex shedding events occuring at near maximum deflection the translatory velocity with associated moving wall effect is very small. In addition, as was pointed out in reference [27], the (moving wall) effects are of opposite signs further diminishing the net effect of these two intermediate vortex shedding events at near maximum deflection.

Thus, one can see how the moving wall effect associated with the translatory oscillations can explain the observed subharmonic response at $f = f_{v0}/3$ and the absence of any response at $f = f_{v0}/2$. What about the superharmonic response? Figure 2 shows how in the case $f = 3 f_{v0}$ every vortex shedding event is enhanced by the moving wall effect, whereas for $f = 2 f_{v0}$ every other event is opposed by the translatory velocity effect. Thus, one would expect that locking-on of the vortex shedding phenomenon is possible at $f = f_{v0}$ and $f = 3 f_{v0}$, but not for $f = 2 f_{v0}$. This is exactly what the results obtained by Stansby [31] show (Fig. 3). There are

lock-ins at $S_c = S_0$ and $S_c = 3 S_0$, but no clear sign of locking-on at $S_c = 2 S_0$.

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