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Literature on flow-induced vibrations of spheres, spheroids, short cylinders and other three-dimensional bluff bodies has been reviewed. Information considered pertinent to the analysis and design of large submerged cable structures subjected to currents in the deep ocean is consolidated and presented in an annotated bibliography. Of particular interest is the vortex shedding from, and vortex-induced motions of and forces on three-dimensional bodies representative of buoys, sensor packages and similar components of mid-ocean arrays. next page

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20. Continued

Since very little information was found that is directly applicable to analysis and design further research is recommended.

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FLOW-INDUCED VIBRATIONS OF THREE-DIMENSIONAL BLUFF BODIES IN A CROSS FLOW, AN ANNOTATED BIBLIOGRAPHY (Final), by R. D. Rail, B. E. Hafen, and D. J. Meggitt
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Literature on flow-induced vibrations of spheres, spheroids, short cylinders and other three-dimensional bluff bodies has been reviewed. Information considered pertinent to the analysis and design of large submerged cable structures subjected to currents in the deep ocean is consolidated and presented in an annotated bibliography. Of particular interest is the vortex shedding from, and vortex-induced motions of and forces on three-dimensional bodies representative of buoys, sensor packages and similar components of mid-ocean arrays. Since very little information was found that is directly applicable to analysis and design further research is recommended.

CONTENTS

I. INTRODUCTION

The Civil Engineering Laboratory, as part of a continuing program of support to the Naval Electronic Systems Command, is investigating the structural and implant dynamics of large suspended cable arrays in the deep ocean. The arrays are large tension-member structures; the tension elements are cables which have diameters of the order of an inch or two, and which may be several thousand feet long. The structures are supported by buoyant floats, which are usually spherical or cylindrical in shape and have diameters and lengths of several feet. The array is the platform for a variety of sensors which are generally housed in packages that are spherical or spheroidal in shape. In addition, flotation packages may be distributed along the tension members.

In place, anchored to the ocean floor, the array is subjected to forces caused by the flow of currents over the structure. From a hydrodynamic point of view, the array may be considered to be comprised of two-dimensional (the cables) and three-dimensional (floats and sensor packages) bluff bodies. Flow around bluff bodies causes forces on and motions of the bodies due to vortex shedding. This motion, which in the case of cables is termed "strumming", causes degraded acoustic and environmental sensor performance and can result in accelerated wear and fatigue on array components. In addition, the hydrodynamic drag of a vibrating body is substantially greater than that of a non-vibrating body, increasing the overall forces on the structure.

The vortex-induced motions of two-dimensional bluff bodies have been extensively studied. A major research program at the Civil Engineering Laboratory is extending this work to elastic cable structures. However, relatively little work has been done on the vortex-induced motions of three-dimensional bluff bodies. This results in substantial uncertainty in the design of arrays and array components. Although the drag of discrete three-dimensional elements is generally a relatively small part of the total array drag, even if amplified by vortex-shedding, the motion of floats or sensor packages may cause serious interference with the sensor outputs. Because of the apparent lack of data for vortex-induced forces on three-dimensional bluff bodies, the Civil Engineering Laboratory has surveyed the available information on this subject to: (1) determine the present state of knowledge of vortex-induced motions of three-dimensional bluff bodies; (2) assess the applicability of existing information to the suspended array problem; and (3) identify those areas in which additional research is required. This technical note presents the results of the investigation.

II. SUMMARY

The study reported herein has shown that there is an extreme lack of information on the subject of vortex shedding from, and vortex-induced motions of, three-dimensional bluff bodies; there are essentially <u>no</u> data which can be directly applied to suspended array design. The limited

data which are available indicate that the vortex-shedding phenomena have the potential for causing serious interference with sensor outputs. In sum, the study has shown that significant uncertainties exist in the design of suspended arrays which have three-dimensional bluff bodies as components.

III. SCOPE

In this report existing information which is considered to be of value in the analysis (prediction of behavior) and the design (provision of desirable structural behavior and the suppression of undesirable behavior) of submerged cable structures subjected to currents in the deep ocean is consolidated. The flow is considered unbounded, uniform, and steady. Since only limited information which can be used directly for analysis and design is available, the literature cited includes related topics to provide a broader background on the origin of flow-induced forces and motions. This includes information on the phenomena of flow about three-dimensional bluff bodies, the transition from laminar to turbulent flow, boundary layer separation, wake formation and vortex shedding behavior.

Geometrical shapes used for three-dimensional array components are generally spheres, prolate spheroids ("footballs") or short cylinders (length to diameter ratios of less than 5 or 6) with flat, hemispherical, or conical ends.

The primary emphasis in this report is on experimental findings, since this comprises the bulk of the research on the subject. The following data banks were searched:

(1) Defense Documentation Center (DDC), classified and unclassified

(2) National Technical Information Services (NTIS)

(3) National Aeronautical and Space Administration (NASA)

(4) Engineering Index (COMPENDIX)

(5) Dissertation Abstracts (DATRIX)

(6) Oceanic Abstracts

(7) Physics Abstracts (INSPEC/PHYSICS)

Only those reports available in English were reviewed.

The citations of the literature reviewed are presented in four appendices:

Appendix A: Bibliography of Flow-Induced Vibrations of Three-Dimensional Bluff Bodies in a Cross Flow

Appendix B: Annotated Bibliography of Flow-Induced Vibrations of Spheres, Spheroids and Other Three-Dimensional Bodies

Appendix C: Annotated Bibliography of Flow-Induced Vibrations of Short Cylinders in a Cross Flow

Appendix D: Annotated Bibliography of Background and Survey Articles on Flow-Induced Vibrations of Three-Dimensional Bodies

Appendix A is an alphabetical listing of all the references cited in this report. Appendices B, C, and D contain annotated abstracts for each citation. In most cases, the summary or abstract prepared by the author of the reference - indicated by "(Author)" following the entry - is used verbatim. Generally, additional information from the reference is provided by the writers of this report. For those cases in which no author's abstract or summary was available, the overall summary was prepared by the writers of this report. In each annotated abstract, the Reynolds number range and body/fluid/test facility combination are stated preceeding the summary. These provide a ready indication of the experimental parameters in the reference.

IV. CONCLUSIONS AND RECOMMENDATIONS

The information contained in the available literature on vortex-induced forces on and motions of three-dimensional bluff bodies is summarized below:

1. The mean drag forces on fixed, non-vibrating spheres have been well documented for both smooth and rough spheres. The drag of vibrating spheres has not been reported quantitatively except for Reynolds numbers less than 3,000.

2. The flow phenomena about a sphere, including vortex shedding and wake configuration, have been studied at moderate Reynolds numbers ($Re \sim 3$-4,000) with free-falling liquid drops and solid spheres, and with fixed spheres up to transition Reynolds number ($Re \sim 1x10^5$ to $3x10^5$).

3. The frequency of vortex shedding from fixed spheres has been measured for Reynolds numbers up to critical ($\sim 2x10^5$).

4. Flow-induced fluctuating lift forces on a fixed sphere and on an oscillating cantilever cylinder, both in supercritical flow, have been reported (Willmarth and Enlow (1969), and Fontenot (1960)). Very little additional information on transverse forces on three-dimensional bluff bodies was found.

5. Various methods for supression of flow-induced motions of a taut-moored submerged cylindrical buoy have been investigated. Splitter

plates, stabilizing vanes and drogues and changes in the mooring configuration reduced motions to an acceptable level (O'Neill, Goeller and Berezow (1973)). Studs and other surface modifications to prevent formation of strong vortices or to disrupt coherent vortex shedding along the cylinder reduced but did not eliminate the motion (Berezow and Sallet (1972)). McEachern (1974) has studied the suppression of flow-induced oscillations of pendulating cylindrical hydrophones by detuning the structural system.

Based on the above observations, the following topics for continued research are recommended to provide a better understanding of the effects of the drag and motion of three-dimensional bluff bodies on a cable structure:

A. Investigation of the vortex-induced forces on and motions of three-dimensional bluff bodies representative of submerged array components to permit an assessment of the importance of this phenomenon to sensor and array performance.

B. Depending on the results of the above study, investigation of means to suppress undesirable motions over the range of Reynolds numbers appropriate to submerged arrays.

Successful conclusion of the suggested research will provide the array designer with a rational means to account for flow effects on three-dimensional bluff bodies, a capability now lacking.

APPENDIX A

BIBLIOGRAPHY OF FLOW-INDUCED VIBRATIONS OF THREE-DIMENSIONAL BLUFF BODIES IN A CROSS FLOW

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APPENDIX B

ANNOTATED BIBLIOGRAPHY OF FLOW-INDUCED VIBRATIONS OF SPHERES, SPHEROIDS AND OTHER THREE-DIMENSIONAL BODIES

(NOTE: In the annotations identified by author, the symbols used by the original authors have been retained although they sometimes differ from those used elsewhere in this report.)

Achenbach, E. (1972)

"Experiments on the Flow Past Spheres at Very High Reynolds Numbers," Journal of Fluid Mechanics, vol. 54, part 3, 1972, pp. 565-575.

Reynolds Number Range: $5x10^4<Re<6x10^6$

Body/fluid/facility System: Sphere/air/wind tunnel

The present work is concerned with the flow past spheres in the Reynolds number range $5x10^4<Re<6x10^6$. Results are reported for the case of a smooth surface. The total drag, the local static pressure and the local skin friction distribution were measured at a turbulence level of about 0.45%. The present results are compared with other available data as far as possible. Information is obtained from the local flow parameters on the positions of boundary-layer transition from laminar to turbulent flow and of boundary-layer separation. Finally the dependence of friction forces on Reynolds number is pointed out. (Author)

The experiments were performed on sting-mounted stationary spheres, about 7 and 8 inches (175 and 200 mm) in diameter, in a high pressure and an atmospheric wind tunnel at Mach numbers less than 0.1 and generally less than 0.05. Local static pressure and skin friction were measured by probes inserted in a rotatable ring-shaped element of the sphere that could be placed in any circumferential position.

The behavior of the boundary layer transition and separation, as deduced from the measured flow parameters about the spheres, are discussed in detail in each of the four flow regimes defined as subcritical, critical, supercritical and transcritical. The Reynolds number ranges for these flow regimes are affected by turbulance, surface roughness, degree of fixity of mounting and other factors, and are thus not sharply de-limited. For fixed smooth spheres in a low turbulence flow field the Re ranges are approximately:

Subcritical flow regime	$Re<3x10^5$
Critical flow regime	$3x10^5<Re<3.7x10^5$
Supercritical flow regime	$3.7x10^5<Re<1.5x10^6$
Transcritical flow regime	$Re>1.5x10^6$

10 references.

Achenbach, E. (1974a)

"Vortex Shedding from Spheres," Journal of Fluid Mechanics, vol. 62, part 2, 1974, pp. 209-221

Reynolds Number Range: $4 \times 10^2 < Re < 5 \times 10^6$

Body/fluid/facility System: Sphere/water/water channel and Sphere/air/wind tunnel

Vortex shedding from spheres has been studied in the Reynolds number range $400 < Re < 5 \times 10^6$. At low Reynolds numbers, i.e. up to Re = 3×10^3, the values of the Strouhal number as a function of Reynolds number measured by Moeller (1938) have been confirmed using water flow. The lower critical Reynolds number, first reported by Cometta (1957), was found to be $Re \approx 6 \times 10^3$. Here a discontinuity in the relationship between the Strouhal and Reynolds numbers is obvious. From $Re \approx 6 \times 10^3$ to $Re \approx 3 \times 10^5$ strong periodic fluctuations in the wake flow were observed. Beyond the upper critical Reynolds number ($Re \approx 3.7 \times 10^5$) periodic vortex shedding could not be detected by the present measurement techniques.

The hot-wire measurements indicate that the signals recorded simultaneously at different positions on the 75^o circle (normal to the flow) show a phase shift. Thus it appears that the vortex separation point rotates around the sphere. An attempt is made to interpret this experimental evidence. (Author)

In the water channel tests the vortex shedding frequency was determined from visual observations of the release of vortices from the sphere for $400 < Re < 3000$.

In the wind tunnel tests the frequency of the unsteady boundary layer separation was detected by hot wire probes flush-mounted on the sphere surface 75^o from the front of the sphere. Although strong signals were detected for $6{,}000 < Re < 300{,}000$, the signals disappeared abruptly both below and above this Re range. The 75^o latitude is a few degrees upstream of the boundary layer separation point in subcritical flow. No measurements were made in the wake of the sphere in the wind tunnel tests.

In the range $6{,}000 < Re < 300{,}000$ it appears that vortex separation occurs at a point and that the point of vortex release rotates about the sphere. Thus the vortices are not released from the sphere in the form of rings. Neither could they be in the form of a single-helix or double-helix system which would be inconsistent with Thomson's circulation theorem.

13 references

Achenbach, E. (1974b)

"The effects of surface roughness and tunnel blockage on the flow past spheres," Journal of Fluid Mechanics, vol. 65, part 1, 1974, pp. 113-125

Reynolds Number Range: $5 \times 10^4 < Re < 6 \times 10^6$

Body/fluid/facility Systems: Sphere/air/wind tunnel

The effect of surface roughness on the flow past spheres has been investigated over the Reynolds number range $5 \times 10^4 < Re < 6 \times 10^6$. The drag coefficient has been determined as a function of the Reynolds number for five surface roughnesses. With increasing roughness parameter the critical Reynolds number decreases. At the same time the transcritical drag coefficient rises, having a maximum value of 0.4.

The vortex shedding frequency has been measured under subcritical flow conditions. It was found that the Strouhal number for each of the various roughness conditions was equal to its value for a smooth sphere. Beyond the critical Reynolds number no prevailing shedding frequency could be detected by the measurement techniques employed.

The drag coefficient of a sphere under the blockage conditions $0.5 < d_s/d_t < 0.92$ has been determined over the Reynolds number range $3 \times 10^4 < Re < 2 \times 10^6$. Increasing blockage causes an increase in both the drag coefficient and the critical Reynolds number. The characteristic quantities were referred to the flow conditions in the smallest cross-section between sphere and tube. In addition the effect of the turbulence level on the flow past a sphere under various blockage conditions was studied. (Author)

d_s/d_t is the ratio of the sphere diameter to the tube diameter.

4 references

Bailey, A.B. (1974)

"Sphere Drag Coefficient for Subsonic Speeds in Continuum and Free-molecule Flows," Journal of Fluid Mechanics, vol. 65, part 2, 1974, pp. 401-410.

Reynolds Number Range: $10^{-2}<Re<10^{7}$

Body/fluid/facility Systems: Sphere/air/ballistic range, and other

An extensive series of measurements of sphere drag coefficients has been made in an aeroballistic range for a broad range of Reynolds and Mach numbers. These measurements have been compared with those obtained in other test facilities. As a result of this comparison it has been possible to suggest reasons for many of the inconsistencies in the earlier measurments and to establish more accurate values of the sphere drag coefficient for $M_\infty<0.2$ and $10^{-2}<Re_\infty<10^{7}$. (Author)

The present study has shown that many of the measurements of subsonic sphere drag obtained to date have been affected by the methods used to obtain them. For example, it has been shown for $Re_\infty>10^{2}$ that (i) translational oscillation of the sphere can cause an increase in the drag, (ii) flow turbulence in the medium through which the sphere is falling results in a decrease in drag, (iii) in some of the free-fall measurements the fall distance has been insufficient for the terminal velocity to have been achieved (consequently, the sphere drag coefficient has been over-estimated) and (iv) for supercritical flow the absolute drag value is affected by flow turbulence and the model mounting technique.

When the above factors have been taken into consideration it has been shown for subcritical flow that most of the earlier data are in reasonable agreement with the results of the extensive aeroballistic-range study of Bailey & Hiatt (1971). For supercritical flow the existing measurements are characterized by considerable spread and the suggested value of C_D is based on one set of free-fall data. To determine the value of C_D in supercritical low turbulence flow it would be desirable to make more free-fall measurements. (Author)

Re_∞ and M_∞ are the free-stream Reynolds and Mach numbers respectively; C_D is the drag coefficient. The other test techniques include spheres free falling or towed in air or liquids or mounted in a wind tunnel or on an airplane.

24 references

Bailey, A. B. And J. Hiatt (1972)

"Sphere Drag Coefficients for a Broad Range of Mach and Reynolds Numbers," AIAA Journal, vol. 10, no. 11, Dec 1972, pp. 1436-1440.

Reynolds Number Range: $2x10^{-1}<Re<10^{6}$

Body/fluid/facility System: Sphere/air/aeroballistic range

The purpose of the present investigation was to establish accurate values of sphere drag coefficient in the flight regime $0.1<M_\infty<6.0$ and $2x10^{1}<Re_\infty<10^{5}$ for $T_w/T_\infty \simeq 1.0$. To this end, an extensive series of measurements was made in a ballistic range. These measurements, together with other published data, permit the derivation of sphere drag coefficients with an uncertainty of $\pm2\%$ in this flight regime. In addition, sufficient information is presented such that reasonable estimates of sphere drag coefficient can be made for $T_w/T_\infty \neq 1.0$, $0.05<M_\infty<20.0$ and $2x10^{-1}<Re_\infty<10^{6}$. (Author)

M_∞, Re_∞ and T_∞ symbolize the free-stream Mach number, Reynolds number and temperature. T_w represents the sphere wall temperature.

The aeroballistic range drag measurements made at low speeds ($M_\infty<0.38$) compare well with "standard" drag curves for $5x10^{2}<Re<10^{4}$, and are somewhat lower for $10^{4}<Re<10^{5}$.

44 references

Bearman, P. W., and J. E. Fackrell (1975)

"Calculation of Two-dimensional and Axisymmetric Bluff-body Potential Flow," Journal of Fluid Mechanics, vol. 72, part 2, 1975, pp. 229-241.

Reynolds Number Range: Various

Body/fluid System: Various bodies/generalized fluid

A numerical method incorporating some of the ideas underlying the wake source model of Parkinson & Jandali (1970) is presented for calculating the incompressible potential flow external to a bluff body and its wake. The effect of the wake is modelled by placing sources on the rear of the wetted surface of the body. Unlike Parkinson & Jandali's method, however, the body shapes that can be treated are not limited by the restrictions imposed by the use of conformal transformation. In the present method the wetted surface of the body is represented by a distribution of discrete vortices. Good agreement has been found between the pressure distributions predicted by the numerical method and the analytic expressions of Parkinson & Jandali for a "two-dimensional" circular cylinder and flat plate. A flat plate at incidence and other asymmetric two-dimensional flows have also been treated. The method has been extended to axisymmetric bluff bodies and the results show good agreement with measured pressure distributions on a circular disk and a sphere. (Author)

14 references

Brabston, D. C., and H. B. Keller (1975)

"Viscous Flows Past Spherical Gas Bubbles," Journal of Fluid Mechanics, vol. 69, part 1, 1975, pp. 179-189.

Reynolds Number Range: $10^{-1}<Re<2x10^{2}$

Body/fluid Systems: Bubble, sphere/generalized fluid

Computations of the steady viscous flow past a fixed spherical gas bubble are reported for Reynolds numbers in the range $0.1<R<200$. Good agreement with Moore's (1963) asymptotic theory for the drag coefficient is obtained for $R>40$ and with the well-known small-R theory for $R<1/2$. The method of series truncation is used to reduce the problem to a nonlinear two-point boundary-value problem, which is then solved by an accurate and efficient finite-difference procedure. (Author)

The computation method is easily adapted to flows past a rigid sphere; results are in good agreement with those of others.

12 references

Calvert, J. R. (1967)

"Experiments on the Low-Speed Flow Past Cones," Journal of Fluid Mechanics, vol. 27, part 2, 1967, pp. 273-289

Reynolds Number Range: $Re \simeq 5 \times 10^4$

Body/fluid/facility System: Cone/air/wind tunnel

The wake behind a cone in incompressible flow has the form of a closed bubble. Measurements of velocity, turbulence and static pressure for various cone angles show that the wakes are all essentially similar. A wake Strouhal number may be defined, which is the same for all the models. A disk may be treated as a cone of 180° vertex angle. (Author)

The experiments on the wakes behind axisymmetric blunt-based bodies were carried out in an open return wind tunnel with a working section 20 x 28 in (510 x 710 mm). The models were supported by a downstream sting and six piano wires. The models included cones with vertex angles of 20°, 40°, 60° and 90° all with base diameters of 2 in. (51 mm); a 2-in. (51-mm) diameter disk, and a 3-in. (76-mm) diameter 9-in (230-mm) long cylindrical model with an ellipsoidal nose and a blunt base. The cylindrical model was treated as a cone of 0° vertex angle. The Reynolds number for most of the observations was about 50,000.

The wakes showed definite periodicities which however were very weak compared to periodicities in the wakes of spheres and circular cylinders at the same Reynolds numbers. The periodicity, which was discernible only in the wake, was most prominent in the region of static pressure maximum and was not detectable upstream of the static pressure minimum. (For a 60° cone, the maximum and minimum pressure regions are about 2.2 base diameters and 0.9 base diameter, respectively, downstream from the base.)

The Strouhal number, based on the cone diameters and free stream velocity, varied from 0.135 for a cone angle of 180° to 0.246 for a cone angle of 0°. For a given cone the frequency did not vary from place to place within the wake. A wake Strouhal number, based on the wake diameter and the velocity just outside the wake, had a constant value of 0.19 for all models tested.

6 references

Calvert, J. R. (1972)

"Some Experiments on the Flow Past a Sphere," Aeronautical Journal, vol. 76, Apr. 1972, pp. 248 - 250.

Reynolds Number Range: $10^4 < Re < 6.5 \times 10^4$

Body/fluid/facility System: Sphere/air/wind tunnel

Measurements are reported of vortex shedding frequency, base pressure, wake dimensions and static pressure in the wake of a 1 7/8-in. (48-mm) sphere (to three sphere diameters downstream). The sphere was supported by a downstream sting and six wires in a wind tunnel with a 20-in x 28-in (510-mm by 710-mm) working section. Experiments were made both with and without a trip-wire at 45° from the front of the sphere.

Without the trip-wire prominent vortex shedding was detected throughout the wake and just outside it. The Strouhal number was 0.188 $\pm$.008 at all points in the wake for all Reynolds numbers in the range measured ($2 \times 10^4 < Re < 6 \times 10^4$). With the trip-wire in place no regular vortex shedding could be detected at any position in and around the wake in the range $1 \times 10^4 < Re < 4 \times 10^4$. For $Re > 3 \times 10^4$ the trip-wire caused an increase in base pressure and caused the wake to move closer to the sphere. The trip-wire did not affect the width of the wake. It appears that the effect of the specific trip-wire used was equivalent to increasing the Reynolds number by a factor of 3 or 4, or, conversely, reducing the critical Re from about 2.5×10^5 to about 6.5×10^4.

5 references

Daugherty, R.L. and A.C. Ingersoll (1954)

Fluid Mechanics, With Engineering Applications, McGraw-Hill, New York, 5th Edition, 1954.

Reynolds Number Range: Various

Body/fluid/facility System: Various

In Chapter 13 this representative textbook presents a discussion of phenomena and forces associated with flow about a submerged three-dimensional body.

Typical curves of drag coefficient as function of Reynolds number are presented for spheres, ellipsoids and other three-dimensional bodies.

Photographs of a bowling ball falling through water show, qualitatively, the effects that a a small patch of surface roughness at the upstream stagnation point of the otherwise smooth ball has on the nature of the boundary layer, the location of the boundary layer transition and separation points, and the size and shape of the wake.

Goin, K.L. and W. R. Lawrence (1968)

"Subsonic Drag of Spheres at Reynolds Numbers from 200 to 10,000"
AIAA Journal, vol. 6, no. 5, May 1968, pp. 961 - 962.

Reynolds Number Range: $2x10^2 < Re < 1x10^4$

Body/fluid/facility System: Sphere/air/ballistic range

Drag coefficients were determined for metal spheres of 1/16-in to 1/4-in (1.6-mm to 6.4-mm) diameter in a ballistic range at subsonic Mach numbers up to M = 0.98 but primarily at $0.2<M<0.6$.

The findings are compared with those of others. The results at M = 0.20 are within 5% of these reported by Lunnon (1928) obtained by dropping spheres in water ($M \approx 0$) and by Wieselsberger (1922) obtained from spheres hung in a pendulum-like manner from the top of a wind tunnel ($M<0.1$).

Compressibility effects were present in the Mach number range of 0.20 to 0.33, particularly at $Re>1,000$. The results for $M>0.2$ differ from those of Heinrich, et al (1965).

4 references

Goldstein, S. (editor) (1938)

Modern Developments in Fluid Dynamics, Clarendon Press, Oxford, 2 vols, 726 pp

Reynolds Number Range: Various

Body/fluid/facility System: Various

This account of theory and experiment relating to boundary layers, turbulent motion, and wakes was composed by the Fluid Motion Panel of the Aeronautical Research Committee (Great Britain) and others, and edited by Goldstein. The book presents and summarizes experimental findings and theoretical developments of many investigations of laminar and turbulent flow of incompressible viscous fluids near and at the surfaces of solids and in wakes.

Although the emphasis is on information of particular interest to aeronautical sciences, this book includes considerable subject matter relevant to the study of flow-induced behavior of three-dimensional bodies used as components of moored subsurface arrays. There is an excellent, clearly-stated summarization of flow around and in the wake of spheres, and some information on the effects of aspect ratio on flow about bluff cylinders. Stationary ring vortices and the shedding of vortex loops in sphere wakes are discussed; there is some information on the relative effects on sphere/fluid interaction of cross-flow mounting (a typical configuration in moored arrays) as compared to sting mounting of spheres (usually preferred in experimental studies of basic phenomena).

Ko, S.C. and W.H. Graf (1972)

"Drag Coefficient of Cylinders in Turbulent Flow", Journal of the Hydraulics Division, Proceedings of the ASCE, HY5, May 1972, pp. 897 - 912.

Reynolds Number Range: (Not applicable)

Body/fluid System: (Not applicable)

Experimental investigations of the effects of turbulence on the drag coefficients of circular cylinders are reported.

A review of previous knowledge of the effects of turbulence on bluff bodies is presented; this includes a brief discussion of the effects of turbulence intensity and turbulence scale on the drag coef-fieient of a sphere, in particular the effect of turbulence on the value of the critical Reynolds number.

20 references

Krumins, M. V. (1972)

A Review of Sphere Drag Coefficients Applicable to Atmospheric Density Sensing, Naval Ordnance Laboratory, Technical Report no. NOLTR 72-34, Silver Spring, MD, Jan 1972, 52 pages (AD 742768)

Reynolds Number Range: $5x10^1<Re<5x10^4$

Body/fluid/facility System: Various

A comprehensive search has been performed on the drag coefficient of spheres in the Reynolds number range from $5x10^1$ to $5x10^4$ and for Mach numbers up to 5. This Reynolds-Mach number range corresponds to the range of interest in the falling sphere technique of atmospheric sensing. In this technique, the knowledge of the sphere's trajectory and its aerodynamic characteristics are utilized to obtain the density of the atmosphere. The presently available data have been collected and analyzed as to their validity and applicability to atmospheric density measurements. A new drag table is recommended for use in these measurements. Since the vehicles used for atmospheric sensing are inflated spherical balloons, the question still remains if a factor needs to be applied to correct the drag data measured on idealized spheres for effects, such as those due to surface roughness, surface temperature, out of roundness, etc. (Author)

The author concludes that the drag coefficient curve is well established for smooth spheres in incompressible flow for the Reynolds number range cited above.

31 references

Magarvey, R. H. and R.L. Bishop (1961)

"Wakes in Liquid-Liquid Systems," The Physics of Fluids, vol. 4, no. 7, July, 1961, pp 800 - 805

Reynolds Number Range: $2 \times 10^2 < Re < 5 \times 10^2$

Body/fluid/facility System: Liquid drops/water/free fall

Evidence is presented to support a stable drop wake configuration consisting of a double row of vortex rings. This wake pattern is observed to be characteristic of liquid drops moving through a disperse liquid phase with Reynolds numbers appropriate to a range of nonoscillating drops. The wake configuration displays a high degree of symmetry and periodicity in the shedding of vortices. The wakes are rendered visible by the scrubbing of an aniline dye from the drop as it passes through the continuous phase. The larger oscillating drops leave wakes in which many rings are present, but the symmetry of the smaller drops is lacking. (Author)

Drops differ from spherical bodies in several ways including deformation of shape, internal circulation and oscillation about an equilibrium shape.

The non-oscillating falling drop had a stationary ring vortex wake for Reynolds numbers from some low threshold value (not reported) up to about 200. As Re increased above 200 periodic shedding of vortices began. For Re values of about 350 to about 600 the wake configuration became a symmetrical double row of vortex rings. Above an Re of about 600 the vortex discharges were less periodic and the wake lost its symmetry. The Strouhal number ranged from about 0.11 at Re = 350 to about 0.13 at Re = 500.

14 references

Magarvey, R.H. and C.S. MacLatchy (1965)

"Vortices in Sphere Wakes," Canadian Journal of Physics, vol. 43, no. 9, Sep. 1965, pp. 1649 - 1656

Reynolds Number Range: $2\mathrm{x}10^2<Re<5\mathrm{x}10^2$

Body/fluid/facility System: Liquid drops/water/free fall

The formation and structure of vortices characteristic of sphere wakes corresponding to a range of Reynolds numbers extending from 200 to 500 have been examined. The manner in which vorticity is released to the free stream has been deduced from the photographic evidence. It has been found that, over the entire range of Reynolds numbers considered, at least part of the vorticity generated in the boundary layer is transferred to the stream by means of an involved sheet. This sheet is distorted continuously by the backflowing fluid and reappears as the demarcating surface of the vortex elements of the wake. The spiraling path was found to be associated with the asymmetry relative to the upstream-downstream axis of the sphere. (Author)

Four modes by which vorticity is transferred to the region immediately behind the drop and subsequently discharged into the stream are described below. (The Reynolds numbers cited should be considered approximate, rather than exact, values).

(1) For $1<Re<200$, there is a stationary "ring" behind the drop followed by a narrow single vortex trail.

(2) For $200<Re<300$, there are two parallel vortex trails and the drop falls in a spiraling path.

(3) For $300<Re<450$, loops are detached alternately from diametrically opposite sides of the wake axis. The drop falls in a zig-zag path. Mutually orthogonal views of the wake show it to be three-dimensional though not axisymmetric; the wake becomes much broader in one plane than in the plane at a 90° angle to the first plane. The magnitude of the alternating deflecting force can be approximated from the direction and velocity of inflow associated with the shedding of each vortex loop, as revealed by photographic evidence.

(4) For a very narrow range of Reynolds numbers ($Re \simeq 300$) overlapping the upper and lower limits of the ranges for double-trail and loop-shedding wakes there is a wake form in which the vorticity is always discharged from the same side of the wake axis; the drop falls in a spiral.

Shedding frequencies were not reported.

21 references

Mair, W.A. and D.J. Maull (1971)

"Bluff Bodies and Vortex Shedding - A Report on Euromech 17"
Journal of Fluid Mechanics, vol 45, part 2, 1971, pp. 209 - 224

Reynolds Number Range: Various

Body/fluid/facility System: Various

European Mechanics Colloquium number 17 was held at Cambridge from 1 to 3 July 1970, when the subject of bluff bodies and vortex shedding was discussed. The following report summarizes some of the papers presented. No formal proceedings of the meeting will be published. (Author)

The authors state that when planning the meeting they had hoped that papers on vortex shedding from axisymmetric and three-dimensional bluff bodies would be offered at the meeting. It seems, however, that very little work was in progress, at least in Europe, on this type of three-dimensional vortex shedding and most investigators were still concentrating on nominally two-dimensional situations. Except for the case of the sphere, there had been little attention given to three-dimensional shapes.

Some experiments have been made by Lozowski, List, Rentsch & Byram on spheroidal models representing hailstones. The minor axis varied from 0.5D to D, where D is the major axis, and measurements were made of lift, drag and pitching moment at angles of incidence from 0 to 90°. The main feature of interest in the results is the critical change that occurs in most cases at a Reynolds number (based on D) in the range $2x10^5$ to $4x10^5$. As the Reynolds number increases through the critical value the drag coefficient falls (as for a sphere), and the coefficients of lift and pitching moment rise, although the details of the changes depend to some extent on the incidence and fineness ratio. When the spheroids were mounted with freedom to rotate about a transverse axis, it was found that autorotation occurred in this critical range of Reynolds number.

During the discussion of this work, Viets described some experiments on freely falling spheres in which the centre of gravity was displaced very slightly from the geometric centre. The motion of these spheres involved a zig-zag wandering superimposed on the vertical descent, accompanied by an oscillatory rotation at the same frequency as the wandering. The suggested explanation is that the bias of the centre of gravity leads to the oscillatory rotation and this rotation then causes an oscillatory side force.

(See also Viets (1971))

Maskell described some experiments on spheres at Reynolds numbers near to the critical range in which a side force had nearly always been found, even though the spheres had not been allowed to rotate. This is yet another illustration of the extreme sensitivity of bluff-body flows to small disturbances, when the Reynolds number is near to the critical range.

Achenbach described experiments on the flow in a tube with a sphere mounted centrally in which both the drag coefficient and the critical Reynolds number increased with increasing blockage. (See also Achenbach (1974b))

21 references

Marble, F. E., W. D. Rannie and E. E. Zukoski (1973)

"Research on Energy Exchange in Nonuniform Flow Fields", Aerospace Research Laboratories, Report ARL 73-0138, California Institute of Technology, Pasadena, CA., Nov. 1973, (AD 771794), pp. 8, 9, 21 and 22

Reynolds Number Range: $2x10^2<Re<3x10^3$

Body/fluid/facility System: Sphere/liquid/free fall

Section II of this progress report summarizes the results of an experimental investigation of the drag of a sphere in a fluctuating translational flow at low Reynolds numbers. The importance of the vortex shedding frequency in correlating drag measurements is demonstrated.

Metal spheres of various specific gravities (2.7 to 13.6) were allowed to free fall through a liquid in a container on a shaking table which could be given vertical oscillations over a wide range of frequencies. The oscillatory motions of the spheres were observed and their terminal velocities determined while under the combined effects of the gravity field and the vertically oscillating liquid.

The amplitude of vibration of the sphere is a function of the amplitude of vibration of the liquid and of the relative densities of the sphere and the liquid.

The fluid oscillation had negligible influence on terminal velocity for Reynolds numbers less than 200 and amplitude of vibrations somewhat less than the sphere diameter.

For 400<Re<3000 the percentage decrease in the terminal settling velocity was found to be a function of the Reynolds number, the ratio of imposed frequency to the Strouhal frequency, and the ratio of the amplitude of sphere vibration to the sphere diameter.

The results indicate that for Re greater than about 300 the mean drag is increased as a result of the oscillation of the fluid, with the greatest increase (up to 25% at Re≃3000) at frequencies near the vortex shedding frequency. Flow visualization confirms that over a wide range of frequencies the vortex shedding frequency locks into the imposed frequency, and it is this non-linear interaction that is the cause of the increased drag.

1 reference

Maxworthy, T. (1969)

"Experiments on the Flow Around a Sphere at High Reynolds Numbers," Journal of Applied Mechanics, Transactions of the ASME, Sep 1969, pp. 598 - 607.

Reynolds Number Range: $6\times10^4<Re<2\times10^5$

Body/fluid/facility System: Sphere/air/wind tunnel

Flow around a sphere for Reynolds numbers between 6×10^4 and 2×10^5 has been observed by measuring the pressure distribution around a circle of longitude under a variety of conditions. These include the effects of laminar and turbulent boundary layer separation, tunnel blockage, various boundary layer trip arrangements and inserting an object to disrupt the unsteady recirculation region behind the sphere. (Author)

Boundary layer separation was not profoundly affected by large tunnel blockage effects.

Increasing the trip wire thickness, placing the "side-trip" wire farther from the sphere mid-plane, and increasing the Reynolds number all produced similar effects: the magnitude of the minimum pressure decreased; the minimum pressure region extended further toward the rear of the sphere; the base pressure increased; and the separation point moved further toward the rear.

The drag coefficient was found to be 0.23 for fully turbulent separation of the boundary layer (due to a trip wire) within the Reynolds number range of 10^5 to 2×10^5. The author suggested that the drag coefficient for a smooth sphere at $Re>10^7$ would also be close to the value of 0.23.

The insertion of a 4-in (100-mm) diameter by 4-ft (1.2- m) long tube in the wake of the 6-in (150-mm) diameter sphere (axis of tube aligned in flow direction) had very little effect on the pressure distribution; this is in contrast to the pronounced effect of a splitter plate behind a cylinder as reported by others.

18 references

Mujumdar, A.S. and W.J.M. Douglas (1970)

"Eddy-shedding from a Sphere in Turbulent Free-streams," Int. Journal Heat Mass Transfer, vol 13, no. 10, Oct 1970, pp. 1627 - 1629

Reynolds Number Range: $5.6\times10^3<Re<11.6\times10^3$

Body/fluid/facility System: Sphere/air/wind tunnel

In this short note the authors discuss eddy-shedding from smooth spheres immersed in both low and high turbulence free streams and report experimental results based on hot-wire measurements in the near wake of a 1¼-inch (38-mm) diameter smooth sphere in a wind tunnel. Findings are compared with those of others.

At a free-stream turbulence level of about 0.5% and for $5.6\times10^3<Re<11.6\times10^3$ the Strouhal number remained constant at about 0.20, a value typical of circular cylinders in cross-flow in the same Re range. When the free stream was made turbulent by grids, no oscillations were detected in the wake by the methods used, thus indicating suppression of eddy-shedding. However, similar experiments with circular and square cylinders under identical flow conditions showed that the cylinders continued to shed eddies without significant change in the Strouhal number even when the stream was highly turbulent.

5 references.

Pao, H.P. and T.W. Kao (1975)

On Vortex Structure in the Wake of a Sphere, Catholic University of America, Hydrodynamics Laboratory, Technical Report no. HY-75-001, Washington, DC, May 1975, 24 pages (AD A014061)

Reynolds Number Range: $4.3x10^3 < Re < 1.74x10^4$

Body/fluid/facility System: Sphere/stratified liquid/tow tank

This paper presents results showing the three-dimensional vortex shedding structure when a sphere is towed at a constant velocity through a stratified fluid. It is found that for small Richardson numbers (weak stratification) and Reynolds numbers in the range from $4x10^3$ to $2x10^4$ the vortex is shed three-dimensionally. The stratification however quickly and effectively inhibits the vertical motion and the initially turbulent wake collapses and reveals the vertically oriented portion of the vortex structure, reminiscent of two-dimensional vortex street behind a circular cylinder when viewed from above. The structure is however distinctly three-dimensional. It is also found that the estimated vortex shedding frequency is in reasonable agreement with previously published results for a sphere in a homogeneous fluid. It is suggested that a weak stratification is an excellent means for revealing the vortex structure of a three-dimensional body in a homogeneous fluid and that the vortex tube in the wake of a sphere in a homogeneous fluid has a close-ended double helical structure. Two branches of the double helix are continuously unwinding in an opposite sense from the formation region. Moveover, the present double helical model satisfies Thompson's circulation theorem in constrast to previously proposed helical models. (Author)

The Strouhal number ranged from 0.14 to 0.22 as the Reynolds number increased from $4.3x10^3$ to $1.74x10^4$.

7 references

Roos, F.W. and W.W. Willmarth (1971)

"Some Experimental Results on Sphere and Disk Drag", AIAA Journal, vol 9, no. 2, Feb. 1971, pp. 285 - 291

Reynolds number Range: $5<Re<10^5$

Body/fluid/facility System: Sphere/liquid/towing channel

The drag on spheres and disks moving rectilinearly through an incompressible fluid has been measured for Reynolds numbers (Re) from 5 to 100,000. Test models were mounted on a carriage which rode along a linear air bearing track system. Tests were performed by towing the models through a channel filled with glycerine-water mixtures. Forces and moments on the models were sensed by strain gage transducers; hydrogen bubble flow visualization was utilized in relating these forces to the unsteady wake flows. Steady drag results agreed with existing data except for the disk at $100<Re<1000$, in which the drag coefficient values were up to 50% below the level of existing data; drag force unsteadiness during steady motion was always <5% for the sphere and <3% for the disk. Sphere drag measurements under constant acceleration from rest showed the apparent mass concept to be valid (at high Re) until the sphere had travelled approximately one diameter, after which the quasi-steady drag (based on instantaneous velocity) showed good agreement with the actual drag. Interference effects of the sting supports used in these tests are discussed. (Author)

This paper is concerned only with drag, however the work reported is part of a program of experimental investigation of the relationship between wake unsteadiness, fluctuating transverse forces and moments acting on the sphere and disk.

30 references

Seeley, L.E., R.L. Hummel and J.W. Smith (1975)

"Experimental Velocity Profiles in Laminar Flow Around Spheres at Intermediate Reynolds Numbers," Journal of Fluid Mechanics, vol 68, part 3, 1975, pp. 591 - 608.

Reynolds Number Range: $1.5\times10^2<Re<3\times10^3$

Body/fluid/facility Systems: Sphere/kerosene/flow tunnel

Normal and tangential velocities in the boundary layer and out into the free stream have been obtained using a non-disturbing flow visualization technique for uniform laminar flow around a sphere. The non-similar data are available in tables at 2.5° intervals from 20° from the front to about 15° past the separation point at Reynolds numbers of 290, 750, 1300 and 3000. Stream functions calculated by LeClair using a numerical solution of the Navier-Stokes equation at $Re\approx300$ are not in good agreement with measured values from 30° to 60°, but are in much better agreement around the separation point. Too few grid points near the sphere, where the tangential velocities rise to a maximum above free-stream values, may account for the difference. (Author)

Some observations of flow about the sphere and in the wake are reported qualitatively. Information is presented on changes in vortex size and shedding frequency, and other flow characteristics with increasing Reynolds numbers. The manner in which vortices were formed and the location in the wake at which vortices formed is described. A rotation in the wake about the axis of symmetry was observed in some instances.

25 references

Torobin, L. B. and W.H. Gauvin (1959)

"Fundamental Aspects of Solids-Gas Flow. Part II. The Sphere Wake in Steady Laminar Fluids," Canadian Journal of Chemical Engineering, vol. 37, no. 5, Oct.. 1959, pp. 167 - 176

Reynolds number range: $5<Re<2.6x10^4$

Body/fluid System: Various

A review is made of the experimental evidence and theoretical considerations evolving from studies of the wake formed by an aerodynamically smooth sphere moving in steady rectilinear motion through a turbulence-free stream. The roles of complex fluid dynamic phenomena which include boundary layer separation, vorticity transfer and those characterized by the Strouhal Number, as well as less evident fine scale processes are presented, with reference being made to pertinent two-dimensional cylinder studies. (Author)

This excellent summary of experimental and theoretical work up to 1959 is a portion of a 5-part series on fundamental aspects of solids-gas flow.

Changes in the characteristics of the sphere wake are described as the Reynolds number increases from some low value up to about $2.6x10^4$. At low Re no wake is apparent. At Re≃10* a stationary vortex "ring" appears and grows in size as Re increases to about 130, at which value the downstream end of the ring begins to vibrate. With increasing Re the oscillations become more severe and, at Re≃500, the ring is detached and streams away at a velocity less than the free stream velocity. The Reynolds number at which the ring is first detached is sometimes referred to as the lower critical Reynolds number and has been reported at values from Re=200 to $Re=10^3$.

In the range $2x10^3<Re<10^4$ the wake has been variously described as interlaced helices, vortex chains, two vortex filaments, a series of discrete vortices, etc.

Conflicting values of the Shrouhal number, ranging from about 0.2 to 2.0, have been reported for the Reynolds number range of 10^3 to 10^4. There may be two modes of fluctuations in the sphere wake in this Re range. One mode may give rise to periodicities with a fairly constant Strouhal number at the lower values of 0.2 to 0.4, while the other mode produces periodicities with a Strouhal number increasing up to about 2.0 as the Reynolds number increases to 10^4.

91 references

*Values given should be considered average or representative rather than precise. For variations of values reported see the article or the original papers.

Viets, H. (1971)
"Accelerating Sphere-Wake Interaction" AIAA Journal, vol. 9, no. 10, Oct 1971, pp. 2087 - 2089.

Reynolds Number Range: $1 \times 10^3 < Re < 1 \times 10^4$

Body/fluid/facility System: Sphere/water/free fall

A flow visualization technique was used to observe a freely falling sphere as it accelerated from rest to a constant velocity. The wake and the motion of the sphere before and during the shedding of the first vortex loop are described.

At intermediate Reynolds numbers both lateral and streamwise fluctuating motions are directly related to asymmetric shedding of the vortex wake. An explanation of the physical mechanism involved is proposed.

6 references

Willmarth, W.W. and R.L. Enlow (1969)

"Aerodynamic Lift and Moment Fluctuations of a Sphere," <u>Journal of Fluid Mechanics</u>, vol 36, part 3, 1969, pp. 417 - 432

Reynolds Number Range: $4.5\times10^5<Re<1.7\times10^6$

Body/fluid/facility Systems: Sphere/air/wind tunnel

Measurements are reported of the fluctuating lift acting on a sphere and the moment acting about the centre of a sphere at super-critical Reynolds numbers ($R>4\times10^5$). The lift and moment fluctuations are random functions of time which scale with the free-stream dynamic pressure and sphere dimensions. The power spectra of the lift and moment also scale with the above parameters and with the Strouhal number, nd/U.* The spectra contain a maximum spectral density at very low frequencies (nd/U<0.0003) and do not reveal appreciable effects of vortex shedding at discrete frequencies.

Hot wire anemometers were placed near the surface but outside the boundary layer along a great circle in the meridian plane in which the lift was measured. The fluctuating velocity component near the surface on the upstream hemisphere in this meridian plane is highly correlated with the fluctuating lift in the same meridian plane. The correlation between the lift and tangential velocity near the surface suggests that the fluctuating lift is produced by the component of fluctuating bound vorticity about the sphere that is normal to the meridian plane in which the lift force is measured. The fluctuating moment measured about an axis passing through the centre of the sphere and perpendicular to the above meridian plane is almost perfectly correlated with the fluctuating lift (the measured correlation coefficients were 0.99 and 1.00). The fluctuating moment coefficient is very small ($\sqrt{\overline{C_m^2}}\approx5\times10^{-4}$)* compared to the fluctuating lift coefficient ($\sqrt{\overline{C_L^2}}\approx6\times10^{-2}$).* The exceptional correlation between the random lift and moment suggests that the unsteady moment about the sphere centre (which can be produced only by shear stress fluctuations) is caused by the fluctuations of bound vorticity (residing in the boundary layer and wake) that are responsible for the unsteady lift. (Author)

18 references

*where n is frequency, d is sphere diameter and U is free-stream velocity
*C_m and C_L are the moment and lift coefficients, respectively.

Willmarth, W.W., N.E. Hawk, and R.L. Harvey (1964)

"Steady and Unsteady Motions and Wakes of Freely Falling Disks"
The Physics of Fluids, vol. 7, no. 2, Feb 1964, pp. 197 - 208

Reynolds Number Range: $1<Re<10^4$

Body/fluid/facility System: Disk/liquid/free fall

The motions and wakes of freely falling disks were studied and it was found that the diverse motions of the disks exhibit a systematic dependence on the Reynolds number Re, and the dimensionless moment of inertia I*. The relation between I* and Re along the boundary separating stable and unstable pitching oscillations of the disk was determined. The Reynolds number for stable motion of a disk with large I* is 100, in agreement with the Reynolds number for stability of the wake of a fixed disk. Slightly unstable disks of large I* were stabilized by reducing the moment of inertia. The highest Reynolds number for stable disk motion was 172. At higher Reynolds numbers the disks exhibited periodic pitching and translational oscillations. The laminar wake behind certain of the oscillating disks consisted of a staggered arrangement of two rows of regularly spaced vortex rings similar to the wake observed behind liquid drops by Magarvey and Bishop. The dependence of the dimensionless frequency of oscillation on I* and Re was determined along the boundary for stable motion and at higher Reynolds numbers when the wake was turbulent. Tumbling motions of the disks were observed when the Reynolds number was large, Re>2000, and I* was greater than a certain value, $I^* \approx 10^{-2}$. (Author)

Disks falling in the stable mode, at $1<Re<100$, had a bound ring vortex (distorted torus) when the liquid was quiescent, and released horseshoe shaped vortex loops in disturbed liquid, although the disk itself did not oscillate.

Disks falling in the regular oscillating mode, at $10^2<Re<10^4$, had a definite frequency of oscillation, n. For $10^2<Re<10^3$ the ratio $\frac{nd}{U}$ (where n is frequency of oscillation, d is diameter of disk and U is mean vertical rate of descent) was dependent on I* and Re; two rows of staggered vortex rings appear in the laminar wake. For $10^3<Re<10^4$ $\frac{nd}{U}$ was dependent on I* but independent of Re; vortices were shed alter- alternately into a turbulent wake.

15 references

Winant, C.D. (1974)

"The Descent of Neutrally Buoyant Floats," Deep Sea Research, vol 21, no. 6, June 1974, pp. 445-453

Reynolds Number Range: $0<Re<1.4x10^3$

Body/fluid/facility System: Sphere/stratified salt water/free fall

The dynamics of a neutrally buoyant float descending from the surface to its level of neutral buoyancy in a stable linearly stratified fluid are considered theoretically and experimentally. When the descent is large compared to the float size, the dynamics can be modeled by balancing the acceleration, buoyancy and drag forces, using a quadratic velocity drag form. A general analytical solution can be found in the phase plane, and several typical solutions are computed. Results of visual and quantitative experiments in a salt-stratified tank were in agreement with the theoretical results. (Author)

There is a brief description of the lateral oscillation and of the wake behavior as the falling sphere decelerates to zero velocity and then oscillates vertically about its neutral buoyancy level in the stratified liquid.

7 references

Zarin, N. A. (1970)

"Measurement of Non-continuum and Turbulence Effects on Subsonic Sphere Drag," University of Michigan, Department of Aerospace Engineering, Report NASA-CR-1585, Ann Arbor, June 1970, 137 pages (N70-31869)

Reynolds Number Range: $4x10^1 < Re < 5x10^3$

Body/fluid/facility System: Sphere/air/wind tunnel

The drag of spheres at Mach numbers from 0.10 to 0.57, Reynolds numbers ranging from 40 to 5000, Knudsen numbers as high as 0.060, and turbulence intensities up to 13% was measured in a continuous wind tunnel utilizing a magnetic suspension system. Stainless steel ball bearings having diameters of from 0.04 in.(1 mm) to 1/4 in. (6.4 mm) were used as models. The effects of free-stream turbulence, compressibility, and gas rarefaction were observed and compared with existing data wherever possible. (Author)

The magnetic suspension system permitted some flow-induced translational oscillations; a reduction in the amplitude of oscillation, by modifying the magnetic suspension technique, resulted in a reduction in drag.

references

APPENDIX C

ANNOTATED BIBLIOGRAPHY OF FLOW-INDUCED VIBRATIONS OF SHORT CYLINDERS IN A CROSS FLOW

Berezow, J. and D.W. Sallet (1972)

An Experimental Investigation of Means to Suppress the Flutter Motion of Elastically Suspended Cylinders Exposed to Uniform Cross Flow, Naval Ordnance Laboratory, Technical Report No. NOLTR 72-6, Silver Spring, MD, Feb 1972, 123 pages

Reynolds Number Range: $8x10^4 < Re < 7x10^5$

Body/fluid/facility System: Short cylinder/water/towing tank

When an elastically supported circular cylinder is brought into steady fluid flow, flutter motions occur when it is subjected to flow velocities which exceed a certain critical velocity. The flow-reduced vibrations can be reduced by modifying the surface of the cylinder. This report discusses the effects of 21 surface modifications on the flow-induced vibrations. It is seen that surface modifications can reduce the amplitudes of the flutter motions. (Author)

In this investigation, the elastically supported cylinder is a submerged moored mine case, 21 inches (530 mm) in diameter and 108 inches (2.7 m) long. This cylinder has positive buoyancy and is restrained from rising to the surface or being swept downstream by a 20-foot (6-meter) long mooring cable which is attached to the lower end of the cylinder. The resulting vibrational system resembles a double pendulum. Detrimental flutter motions occur when the moored system is subjected to currents which exceed a certain critical velocity.

Surface modifications had solved a similar flutter problem in air, but tests of the surface modifications reported herein showed only a limited diminishing of the flow-excited vibrations in water.

11 references

Fontenot, L.L. (1960)

The Response (Including Effects of Random Vortex Shedding) of the SM-65E Missile Erected in the Launcher During a 60-MPH Wind, General Dynamics Corporation, Convair Astronautics Division, Report No. AE60-0233, San Diego, CA April 1960 (AD829646)

Reynolds Number Range: Supercritical, $Re \simeq 10^6$

Body/fluid/facility System: Short cylinder/air/wind tunnel and free atmosphere

An analytical approach, based on experimental data of others, was used to determine the loading that a 60-mph (100- km per hr) wind, including random vortex shedding, imposes on the SM-65E missile when in an upright position on the ground prior to launching.

The upright missile is essentially a cylinder cantilevered in a cross flow. Since its diameter is large a Reynolds number of 300,000 is exceeded for wind speeds greater than 3 miles per hour (5 km per hr). Thus, any large oscillations would occur at Re above the critical Re. In the transcritical range the cylinder is subjected to an oscillatory lift force comparable in magnitude to the mean drag force and an oscillatory drag force superposed on the steady mean value. The force input is random; the cylinder will respond substantially at or near to its own fundamental frequency, but with varying amplitude. The amplitude increases indefinitely with increasing wind velocity.

The missile response was analyzed both with full and with empty propellent tanks. Maximum bending moments and shears at the missile base occur with the tanks full. In this case the oscillatory lift and drag due to random vortex shedding increases moments and shears to about twice the moments and shears due to steady drag alone. However, in the empty tank case the moments and shears including the vortex-induced effects are only slightly larger than those due to steady drag. Maximum deflection occurs in the lift plane (transverse to the flow). Responses are greatly influenced by the degree of damping in the system.

In the model tests cited by the author it was found that changing the nosecone or placing spoilers near the tip causes considerable change in lateral deflections and base bending moments. A blunt nosecone increases moments considerably above these produced with a sharper nosecone.

5 references

Gowda, B.H. Lakshmana (1975)

Some Measurements on the Phenomenon of Vortex Shedding and Induced Vibrations of Circular Cylinders, Technische Universitaet Berlin, Deutsche Luft- and Raumfahrt, Forschungsbericht DLR-FB-75-01, 1975, 31 pages (AD B001 388)

Reynolds Number Range: $10^3 < Re < 10^4$

Body/fluid/facility System: Cylinder/air/wind tunnel

This investigation is concerned with vortex-induced self-excited vibrations of circular cylinders in a Reynolds number range around 1000. The influence of finite aspect ratios on the frequency behavior is investigated. The results indicate, to a limited extent, the effects of mass and damping parameters on the general behavior of the system during resonance. Measurements are also presented which show the influence of aspect ratio on vortex shedding from stationary cylinders in a Reynolds number range between 1,000 and 10,000. (Author)

Circular cylinders of differing diameters and mass were subjected to three-dimensional flow immediately downstream from the rectangular exit nozzle of an open jet wind tunnel. The span length of the cylinders was somewhat greater than the nozzle width. Aspect ratio, as used here, is the ratio of the width of opening of the exit nozzle to the cylinder diameter (and thus should not be thought of as the ratio of cylinder length to cylinder diameter).

For aspect ratios less than about 40 there is a decrease in the Strouhal number as aspect ratio decreases. Also, resonance is initiated at a lower ratio of f_v to f_o as the aspect ratio decreases (where f_v is the vortex shedding frequency and f_o is the natural frequency of vibration of the cylinder).

An increase in mass reduces the peak amplitude of vortex-excited vibrations. When both mass and damping are increased not only the peak amplitude is reduced but also the range of the ratio f_v/f_o at which resonance occurs is also reduced.

27 references

Humphrey, S.A. (1973)

"CAPTOR and Future Developments" (U), SECRET, in Proceedings of the 16th Technical Conference of the Naval Minefield Community (U), Naval Ordnance Laboratory, Technical Report No. NOLTR 73-73, June 1973, SECRET, pp. 73-96 (AD 528045L)

Reynolds Number Range: Various

Body/fluid/facility System: Short cylinder/water/towing tank

This paper includes comments on model tests conducted in a circulating water tank to study means of stabilizing moored cylindrical bodies subjected to a cross flow.

McEachern, J. F. (1974)

Suppression of Flow Induced Oscillations of Cylindrical Hydrophones by Detuning, Naval Air Development Center, Report No. NADC-73229-20, Warminster, PA, March 1974 (AD 920429)

Reynolds Number Range: $1x10^2 < Re < 2x10^3$

Body/fluid/facility System: Short cylinder/water/towing tank

The dependent parameters of a simulated hydrophone, suspended as a pendulum in a typical water flow field, are examined. The tuned excitation that results when the vortex shedding frequency and the natural frequency of the pendulum correspond, are of particular interest. Application of the results to contemporary sonobuoy developments are discussed. (Author)

The author concludes that, for Reynolds numbers between 100 and 2,000:

"1. Scaling laws of Meier-Windhorst can be applied to pendulum systems having a right circular cylinder as a terminal body immersed in uniform flow.

2. A pendulum system has a wider amplitude response curve than a one-degree-of-freedom system.

3. As the terminal mass approaches neutral buoyancy, the width of the critical velocity range increases and peak amplitude increases.

4. Detuning is a practical method for stabilizing cable suspended cylinders in a flowing fluid."

9 references

O'Neill, J.J., J. E. Goeller and J. Berezow (1973)

Dynamic Motion of Bottom Moored Mine Cases Exposed to High Current (U), Naval Ordnance Laboratory, Technical Report No. NOLTR 72-123. Silver Spring, MD, June 1973, 58 pages, CONFIDENTIAL (AD 526-879)

Reynolds Number Range: Various

Body/fluid/facility System: Short cylinder/water/various

This report contains the results of model tests conducted to investigate the dynamic motion of cylindrically shaped mines moored to a bottom anchor and exposed to high current. The tests were conducted in laboratory facilities at the Naval Ordnance Laboratory and the Naval Ship Research and Development Center. The cylindrical cases experience rather high tilt angles due to the hydrodynamic drag on the case and the hydrodynamic alternating force caused by vortex shedding. Various ways were investigated to minimize the motion. Both subsize model tests and full-size tests were conducted. (Author)

Froude law modeling of submerged taut moors is discussed in the text and in Appendix A.

2 references

Sallet, D.W. (1969)

"On the Self Excited Vibrations of a Circular Cylinder in Uniform Flow", The Shock and Vibration Bulletin, Bulletin 40, part 3, Dec. 1969, pp. 303 - 309

Reynolds Number Range: $4x10^4<Re<2.7x10^5$

Body/fluid/facility System: Short cylinder/water/towing tank

When an elastically supported circular cylinder is brought into steady fluid flow, flutter vibrations will occur if the fluid velocity relative to the cylinder exceeds a certain value. This flutter problem has received ample attention by various investigators using a variety of physical configurations in their experiments. In most of these flutter investigations the average density of the cylinder is significantly different from that of the fluid and the Reynolds number is well below $Re_{crit}=2x10^5$. This report discusses the influence which the densities and the change in flow regime have upon the flutter motions and describes experimental results of tests at high Reynolds numbers in which the average densities of the cylinder and the fluid differ only slightly. It was found that the cylinders do not any longer exhibit a unique response amplitude and frequency for a given fluid approach velocity but will undergo flutter motions over large amplitude and frequency ranges. These multivalued amplitude and frequency ranges increase as the average density of the cylinder approaches the density of the fluid to which the cylinder is exposed. (Author)

In the experiments cited in this report, submerged, slightly buoyant circular cylinders with length to diameter ratios of approximately 5 and densities (compared to water) of 0.78 and 0.91 were towed through the body of still water at velocities up to 1.7 feet per second (0.5 m per sec). The tethered cylinders responded in a pendulum-like manner. The natural frequency of the systems was varied by changing the lengths of the suspending cables. The induced motions were filmed.

9 references

Sallet, D. W. (1970a)

"A Method of Stabilizing Cylinders in A Fluid Flow," Journal of Hydronautics, vol 4, no. 1, Jan 1970, pp. 40 - 45

Reynolds Number Range: Subcritical and supercritical

Body/fluid/facility System: Short cylinder/water/towing tank

The stability of a slightly buoyant, finite (length $\sim$ 5 diameters) circular cylinder partly restrained (tethered) in a uniform flow was investigated. An analytical expression was derived which relates the location of vortices, vortex strength, and relative velocity of the vortices to the length of the splitter plate necessary to isolate opposing vortices. Four different assumptions are made to calculate the splitter plate length in an effort to bracket the actual value required and to determine which assumptions are relevant.

Experiments were performed with rigidly attached splitter plates of various lengths. It was found that, for subcritical Reynolds numbers, a splitter plate length of 3 diameters suppressed the flutter of the pendulum-like cylinder/tether system. (A length of 2 diameters appeared to support rather than suppress oscillations.) However, when Reynolds numbers were well above the critical value a splitter plate length of only 1.5 diameters was sufficient to suppress all vortex induced motions.

22 references

Sallet, D.W. (1970b)

"On the Reduction and Prevention of the Fluid-Induced Vibrations of Circular Cylinders of Finite Length," The Shock and Vibration Bulletin, Bulletin 41, part 6, Dec 1970, pp. 31 - 37

Reynolds Number Range: $4\times10^4<Re<2.8\times10^5$

Body/fluid/facility System: Short cylinder/water/towing tank

A brief review of the potential flow model of a cylinder in a uniform two-dimensional flow with point vortices is presented. Stability criteria for the vortices are presented, and a splitter plate is shown to enhance stability and prevent the familiar von Karman vortex street.

Experiments are reported in which submerged, slightly buoyant right circular cylinders with length to diameter ratios of 5 were towed through still water by cables of various lengths. Findings are presented graphically which show that the amplitude of flutter of the cylinder cable systems is reduced by 85% to 95% when a splitter plate three cylinder diameters in length is employed. Within the range of variables studied, the splitter plate reduces vibrations to the same degree regardless of the natural frequency of the system. The splitter plate need not be continuous; it appears to be more important that the plate be placed in the neighborhood of 3 diameters downstream from the cylinder. The splitter plate must be free to swing around to the downstream face of the cylinder, otherwise it may cause lift forces.

8 references

Sallet, D.W. and J. Berezow (1972)

"Suppression of Flow-Induced Vibrations by Means of Body Surface Modifications," The Shock and Vibration Bulletin, Bulletin 42, part 4, Jan 1972, pp. 215 - 228

Reynolds Number Range: $8x10^4 < Re < 7x10^5$

Body/fluid/facility System: Short cylinder/water/towing tank

The flow-induced vibrations of an elastically supported cylinder which is exposed to crossflow can be reduced by two methods. One method is to change the parameters of the vibrational system in such a fashion that the approach velocity never equals or exceeds the critical velocity, i.e., the velocity at which large amplitudes start to occur; and the second method is to reduce the flow-induced vibrations by changing the flow around the cylinder, i.e., to change the surface of the cylinder. This report discusses at length the effects of surface modifications on the flow-induced vibrations. It is seen that surface modifications can reduce the amplitudes of the flutter motions. (Author)

The buoyant tethered cylinders oscillated in different modes, as a simple pendulum and as a compound pendulum. Frequency of vibration of the cylinder/tether system was changed by varying the length of the tether, the mass of the cylinder, the net buoyant force, and the separation distance of the centers of gravity and of buoyancy. Graphs are presented relating these system parameters with the critical free field velocity (that velocity at which large amplitude flutter occurs). More than one critical velocity was identified.

The effects on amplitude of vibration due to the various surface modifications are also presented graphically. Certain modifications substantially reduced the amplitude of flutter motions, particularly at the higher critical velocities, but none of the modifications tested was successful in reducing the flutter to insignificant values.

In the discussion following presentation of this paper the senior author mentions that care must be taken in applying wind tunnel data to water flow; methods which reduce flutter in air often do not reduce the same type of vibration in water.

9 references

APPENDIX D

ANNOTATED BIBLIOGRAPHY OF BACKGROUND AND SURVEY ARTICLES ON FLOW-INDUCED VIBRATIONS OF THREE-DIMENSIONAL BODIES

Berger E. and R. Wille (1972)

"Periodic Flow Phenomena," Annual Review of Fluid Mechanics, Van Dyke, M., et al, editors, Palo Alto, CA, 1972, pp. 313 - 340

Reynolds Number Range: Various

Body/fluid/facility System: Various

In this review paper, the authors discuss flows in which the periodicity is a natural phenomenon; the major emphasis is on flow past bluff bodies, primarily circular cylinders both stationary and vibrating. There is very little discussion of spheres and short cylinders. The authors state that results obtained from infinitely long cylinders hold true for finite length cylinders of aspect ratios greater than five.

79 references

Krzywoblocki, M. Z. von (1966)

"Vortex Streets in Fluids," Applied Mechanics Surveys, Abramson, H. N., et al, editors, Sparton Books, Washington, D.C. 1966, pp. 885 - 892

Reynolds Number Range: Various

Body/fluid/facility System: Various

The work of a very large number of investigators of vortex streets in fluids is succinctly summarized. Topics include stability of vortex streets, frequency of vortex formation, edge tones, secondary vortices, relation of vortex streets to turbulent wake, three-dimensional vortex rings, singing of propellors, hydraulic analogy experiments, experimental methods and recent theory of vortex streets.

Of the small amount of work reported on flow past three-dimensional bodies, most is concerned with vortex rings at low Reynolds numbers. Other three-dimensional investigations include studies of frequency of vortex shedding behind spheres, discs and various bodies in air and water.

This review is a revision of that published in the September 1953 issue of Applied Mechanics Review; a more detailed review is contained in the author's Technical Memo, no. 1552, June 1953, issued by the Naval Ordance Test Station, China Lake, CA.

235 references

Rosenhead, L. (1953)

"Vortex Systems in Wakes", Advances in Applied Mechanics, vol 3, R. von Mises, et al, editors, Academic Press, New York, 1953, pp. 185-195

Reynolds Number Range: $Re<5x10^5$

Body/fluid/facility System: Various

The object of the review paper is to assess the basic content of many theoretical and experimental papers which have been written about wakes. Comments are made on three-dimensional vorticity, width of vortex street, frequency of vortex shedding and drag.

A qualitative summarization is presented for information on wakes behind three-dimensional objects, in particular a sphere and a disk. At low Re, in place of the vortex line pair, a vortex ring appears. A cylindrical sheet trails downstream. The sheet is unstable; photographs from mutually perpendicular directions show the discharge of distorted loops of vorticity arranged with some measure of symmetry. The orientation of the planes of symmetry appears to be random; no helical discharge is observed. At higher Re the vortex sheet and the vortex loops diffuse very rapidly; behind the body there can usually be seen a sheath of discontinuity along which corrugations travel in an irregular manner. At still greater Re the flow becomes completely turbulent; there is no longer a systematic arrangement of vortices in the wake.

The author cites the need for a quantitative theoretical treatment and suggests experimental investigation behind three-dimensional bodies.

60 references

Wille, R. (1960)

"Karman Vortex Streets", Advances in Applied Mechanics, vol 6, Dryden, J. L. et al, editors, Academic Press, New York and London, 1960, pp. 273 - 287

Reynolds Number Range: Various

Body/fluid/facility System: Various

A review is presented of the phenomenon of periodic vortex shedding from a symmetrical bluff body. Stability theory, other theories on vortex streets, experimental investigations of vortex streets, and related topics (e.g., pressure distribution) are discussed with emphasis on the period between 1952 and 1960 (i.e. subsequent to the review of Rosenhead (1953)).

36 references

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