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J. P. Gore
Associate Editor

Roughness and Turbulence Effects on the Surface Pressure over Yawed Cylinders

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Nomenclature

AR	= aspect ratio measured perpendicular to airstream
B	= blockage ratio
Cp	= coefficient of pressure $(P - P_\infty)/q$
d	= outer diameter of cylinder
k	= roughness height
q	= freestream dynamic pressure
Re_n	= Reynolds number based on cylinder diameter and freestream velocity
Tu	= turbulence intensity
θ	= circumferential angular position from stagnation position
Λ	= yaw angle

Introduction

THE effects of freestream turbulence and surface roughness on mean and fluctuating surface pressures over a circular cylinder placed perpendicular to the airstream is an active research area in modern aerodynamics.[1,2] Of particular interest is the resulting nature of the flow over a yawed circular cylinder when such secondary effects are applied. This Note documents tests over smooth and rough 45-deg yawed circular cylinders in both smooth and turbulent freestreams. Results from investigations show that mean pressure over the model in all configurations established infinitely long circular cylinder conditions over part of the span. Results from fluctuating pressure distributions, however, showed no sign of infinitely long circular cylinder conditions except in a turbulent freestream. The increased ability of the turbulent freestream to generate infinitely long circular cylinder conditions is thought to be due to the increased mixing and entrainment with which a turbulent freestream imparts to the separating shear layers, reducing the effect of the exposed free end. Results from the roughened model showed highly asymmetric fluctuating pressure distributions, further indicating that both the mean and fluctuating pressures should be considered if infinitely long circular cylinder conditions are required.

Experimental Arrangement and Procedure

All tests were conducted in an open-circuit, closed-test-section, low-turbulence (0.2% at 40 m/s) wind tunnel on yawed circular-cylinder models at a Reynolds number of 9.6×10^4. Three flow configurations were analyzed: a smooth model ($k/d < 10^{-5}$) in low freestream turbulence (denoted as *smooth*), a smooth model in grid-generated turbulence (denoted as *turbulent*), and a roughened model in low freestream turbulence (denoted as *rough*). To simulate the turbulent flowfield, a square-mesh, biplanar, turbulence-generating grid was placed between the outlet of the contraction and the entrance to the test section. The grid was composed of circular cross-section rods 2.5 mm in diameter and spaced at 25-mm intervals. The longitudinal turbulence intensity and integral length scale for this flow configuration were measured at the model station using a hot-wire anemometer at 2% and 14 mm, respectively. The upstream end of the model was 12 mesh spacings downstream from the meshed grid, ensuring that the model was in homogeneous turbulence.[3] Roughness was simulated by covering the entire span of the model with Norton 60-grit emery paper. Holes of 1-mm diameter were carefully punched into the emery paper to coincide with the pressure tap holes in the model. The relative roughness of the paper was estimated to be $k/d = 500 \times 10^{-5}$.

The yawed circular cylinder basic model configuration is shown in Fig. 1. The models spanned the 457 × 457 mm test section and were mounted 30 mm off the tunnel walls using support blocks. The test section blockage ratio B and model aspect ratio AR (measured perpendicular to the airstream) were kept constant for all configurations at 10% and 10, respectively. Having these conditions for

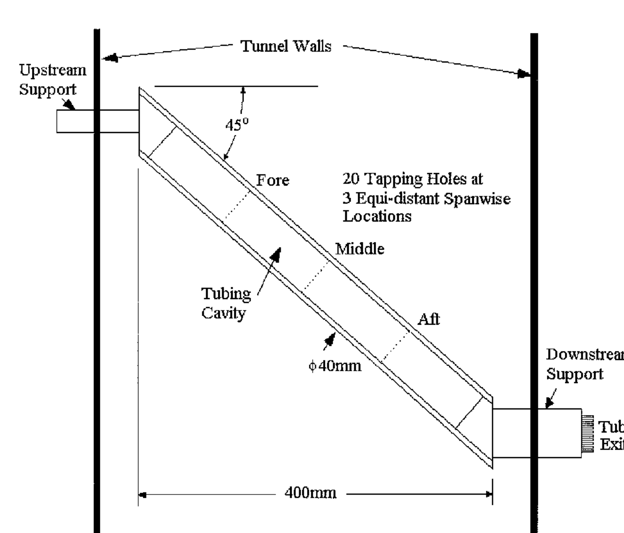

Fig. 1 A 45-deg yawed circular cylinder: flow direction, top to bottom of page.

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all models allowed the effects of surface roughness and freestream turbulence to be isolated. Three equidistant measurement locations along the model span, each with an array of 20 equidistant circumferential pressure tapping holes, were analyzed. Measurements of the mean and fluctuating surface pressures were obtained using the technique outlined in Ref. 4. The accuracy of the system was ±0.1 in 1.5 of Cp and ±0.03 in 0.45 of $Cp_{\rm rms}$. All results were repeatable to within ±0.075 in 1.5 of Cp and ±0.03 in 0.45 of $Cp_{\rm rms}$.

Results and Discussion

The coefficient of mean pressure distribution is shown in Fig. 2. Good agreement is achieved with the published results of Bursnall and Loftin[5] for the middle and aft measurement locations. Agreement was, however, severely affected by up to 40% in magnitude at the fore position due to the proximity of the free end. This disagreement is not surprising due to the results of Bursnall and Loftin being obtained with no exposed model free end. A similar trend is found for cantilevered circular cylinders flows. Results from West and Apelt[6] show that this increase in the surface pressure occurs from the downwash flow over the end, through the generation of two symmetrical longitudinal vortices. The generation of these vortices for the rough condition at the fore position was found, however, to be asymmetric due to differences of up to 50% in the pressure distributions between $0 < \theta < 180$ deg and $180 < \theta < 360$ deg. Results from the turbulent flow case show a decrease in mean pressure magnitude in the angular region extending from $80 < \theta < 280$ deg. Such a decrease is consistent with trends found in nonyawed circular cylinder turbulent flows,[1] from a reduction in wake size through delayed separation. The agreement in the results at the middle and aft positions for all flow configurations show that the flow is free of end effects and consistent with infinitely long model flow conditions.[7]

Results shown in Fig. 3 for the smooth condition show differences of 30–35% in fluctuating pressure magnitudes in the angular region extending from 140 to 280 deg for the middle and aft positions. In the turbulent flow condition, results for the middle and aft measurement positions are symmetrical and in good agreement. From these results, the influence of increasing freestream turbulence is clearly to promote infinitely long model conditions through the increased mixing, delayed flow separation, and a decreased wake size.[1] This mechanism would give the flow increased ability to attain infinitely long model conditions from a reduced wake at the free end. Increases in pressure fluctuations at the fore position support this finding. For the rough condition, highly asymmetric fluctuating pressure distributions for the middle and aft positions were found. Similar asymmetry has been found in nonyawed circular cylinder flows and results primarily from asymmetric boundary-layer transition.[2]

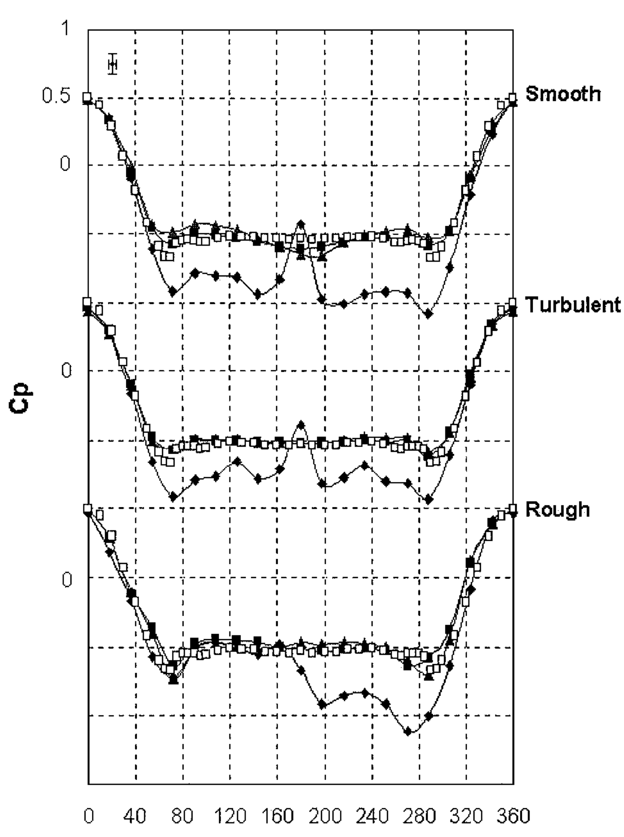

Fig. 2 Mean pressure distribution over the 45-deg yawed circular cylinders, $Re_n = 9.6 \times 10^4$: ◆, fore position; ▲, middle position; ■, aft position; and □, Bursnall and Loftin,[5] $Re_n = 2.5 \times 10^4$, $\Lambda = 45$ deg.

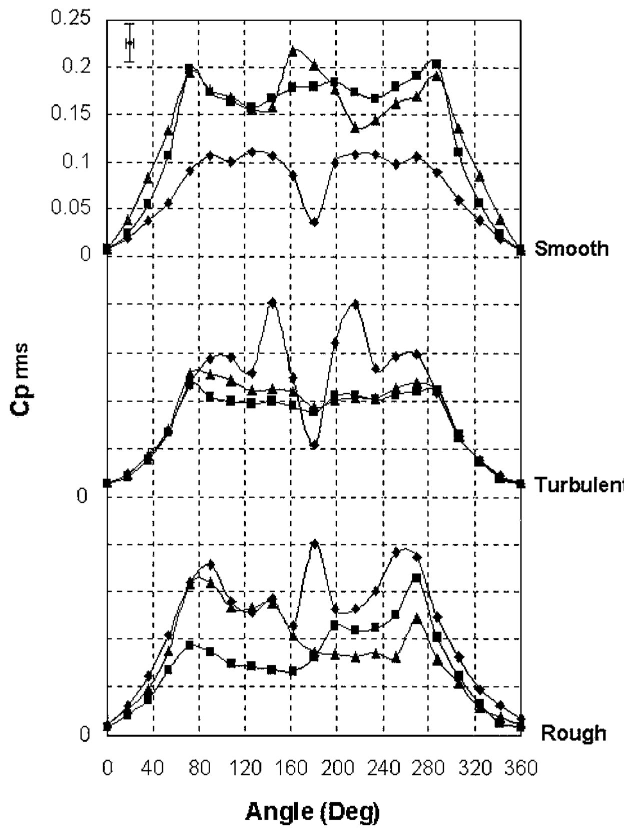

Fig. 3 Fluctuating pressure distribution over the 45-deg yawed circular cylinders, $Re_n = 9.6 \times 10^4$: ◆, fore position; ▲, middle position; and ■, aft position.

Conclusions

A mean and fluctuating surface pressure analysis over both smooth and rough 45-deg yawed circular cylinders in low and moderate turbulent freestreams are presented. Results from mean pressure distributions indicate that infinitely long model conditions are established away from the disturbance of the free end. With the exception of the turbulent flow results, fluctuating pressure distributions show flow conditions not independent of span, suggesting that both mean and unsteady flow characteristics must be considered if infinitely long model conditions are required. Increasing freestream turbulence was found to promote infinitely long circular cylinder results, whereas surface roughness was found to produce highly asymmetric, unsteady flow results.

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Probabilistic Approach for Integrated Structural Control Design

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Introduction

DURING the development phase of a new engineering project, the design requirements and the project variables are usually defined in a deterministic sense, and, for robustness considerations, the uncertainty of the parameters is considered to occur around their design value by means of simplified models. Sufficient conditions must then be satisfied to achieve confidence in the quality of the final design. To meet the requirement constraints, a control strategy can be integrated within the structural design process so that the design of the structure and that of the control system are developed in parallel. The use of a classical robust control system design may be properly employed in the case where the problem at hand is convex and sufficient conditions can be met. In this case, however, the real distribution of the random variables involved in the design is not considered.

As an alternative, we suggest considering the problem of integrating the control and structure design within an appropriate probabilistic framework in order to take into account, with a high degree of accuracy, the project constraints and the system uncertainties. This approach implies the possibility of modeling the design parameters as random variables in order to guarantee that a given probability of satisfying the design requirements may be obtained. In many cases, the design through probabilistic constraints is performed with the hypothesis of normal distribution of the involved variables,[1] even if this hypothesis may be too strong an assumption. A better model is possible using some theoretical results that were first obtained in the field of structural reliability in civil and offshore engineering. These results led to the definition of the so-called classical structural reliability methodologies. These methodologies allow one to properly take into account the correct probability distribution function of the design variables and, due to an asymptotic approximation, to perform a set of highly informative evaluations with a low computational cost.

In this way, it is possible to avoid failures in the design strategy in the case of nonconvex problems and to apply an appropriate design procedure even when sufficient conditions are not met. As a result, one should be able to solve a larger class of problems and to assess the quality of the design by obtaining the actual probability of satisfying the design requirements.

Probabilistic Environment

An important aspect connected to a probabilistic formulation of the problem lies in the possibility of properly choosing the controller configuration within a set of different controllers that equally satisfy the same deterministic requirement. Because of the presence of uncertainties in the problem, the controllers do not satisfy the design requirement in the same way, but they do satisfy with a certain probability. For this reason, the best controller may be defined as the one which has the highest probability of satisfying the design requirements.

We start by defining the probability that the event of interest takes place as

$$P = \int_D f_X(\boldsymbol{x}, \boldsymbol{p})\, \mathrm{d}x \tag{1}$$

where $\boldsymbol{p} = (p_1, p_2, \ldots, p_m)^T$ is a deterministic parameter vector and $f_X(\boldsymbol{x})$ is the probability density function of the random variable vector $\boldsymbol{X} = (X_1, X_2, \ldots, X_n)^T$. Actually, P represents the probability of not complying with the design requirements. The domain of integration of $f_X(\boldsymbol{x})$ is $D = \{g(\boldsymbol{x}, \boldsymbol{p}) \leq 0\}$, where $g(\boldsymbol{x}, \boldsymbol{p})$ is the limit state function having the properties that $g(\boldsymbol{x}, \boldsymbol{p}) > 0$ denotes the favorable states, $g(\boldsymbol{x}, \boldsymbol{p}) = 0$ the limit state, and $g(\boldsymbol{x}, \boldsymbol{p}) \leq 0$ the unfavorable states. The domain region D is referred to as the admissible region. From a practical standpoint, Eq. (1) can be rather difficult to evaluate, especially when the uncertainty space is of high dimensions or when the limit state function is of a complex nature. For these reasons, analytical results are hard to find. A possible choice would be to execute Monte Carlo simulations, i.e., to solve Eq. (1) numerically. Another possibility is to use some of the efficient methods that have been developed in the last two decades in the field of structural reliability engineering to approximate the evaluation of P. These methods are referred to as first- or second-order reliability methods (FORM and SORM[2]).

In essence, these methods reduce the cumbersome task of integrating Eq. (1) to that of locating the most probable point in the admissible region. The idea is that of using a set of simple algebraic manipulations to transform the problem in such a way that an exact or asymptotic result may easily be obtained. The key result is this: if the variables X_i are jointly normal distributed and the limit state function is a hyperplane in the form

$$g(\boldsymbol{X}) = a_0 + \sum_{i=1}^{n} a_i X_i := \boldsymbol{a_0} + \boldsymbol{a}^T X \tag{2}$$

then an analytical solution of Eq. (1) is given by

$$P = \Phi(-\beta) \tag{3}$$

where β is known as the reliability index and is defined by the equation

$$\beta := \frac{a_0 + \boldsymbol{a}^T E[\boldsymbol{X}]}{\sqrt{\boldsymbol{a}^T C_X \boldsymbol{a}}} \tag{4}$$

In Eq. (4), $E[\boldsymbol{X}]$ is the vector of the expected values, C_X is the covariance matrix of $\boldsymbol{X}$ and $\Phi(\cdot)$ is the standard normal probability distribution function. Note that if the basic variables X_i are independent standard normally distributed (in this case we will denote them by $\boldsymbol{U}$), β is still given by Eq. (4) with $E[\boldsymbol{U}] = 0$ and $C_U = I$, where I is the identity matrix.

Moreover, if the limit state function is not linear in $\boldsymbol{X}$, the problem may be approximated as[3]

$$P \approx \Phi(-\beta) \tag{5}$$

with

$$\beta = \|\boldsymbol{u}^*\| := \min\{\|\boldsymbol{u}\|\} \text{ for } \{\boldsymbol{u} \mid g(\boldsymbol{u}) \leq 0\} \tag{6}$$

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