Resistance in Unsteady Flow – Search for a Model

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LONG-TERM GOAL

To devise a physics-based model through the use of analytical, numerical, physical, and thought experiments for the prediction of flow-induced unsteady forces on bluff bodies immersed in time-dependent flows. The new model is expected to replace the Morison equation (hereafter called the MOJS equation) and offer greater universality, particularly in the inertia/drag regime, in calculating forces and dynamic response of cylinders in sinusoidal and non-sinusoidal flows.

OBJECTIVES

The initial objectives of this research were: (i) To examine the merits and shortcoming of the existing unsteady-flow force-prediction models, and (ii) To assess the assertion that "the viscous drag force and the inviscid inertia force operate independently and therefore it is possible to divide the measured time-dependent force into two distinct components: an inviscid inertial force and a viscous drag force" (Lighthill, 1986). Extensive calculations have proved Lighthill's proposal to be incorrect. Instead, the objective of the investigation became the development of a three-term MOJS equation: A velocity-square-dependent drag, an acceleration-dependent inertial force, and a second-order correction to the inertial force, without introducing any new empirical coefficients. This objective has been achieved.

APPROACH

The basic approach was to analyze approximately 3,000 force-time records, obtained in the course of experiments with smooth and sand-roughened circular cylinders (Sarpkaya, 1976, 1986), and to devise a model equation which would represent the data with as much precision as possible, for all values of the Keulegan-Carpenter number Kc, Reynolds number Re (or β = Re/Kc), and the relative roughness k_s/D, with the following constraints: (a) the model should be fluid-mechanically and intellectually satisfying; (b) it should address to most of the shortcomings of the MOJS equation and should have distinct advantages over it; (c) it should only contain the drag and inertia coefficients (C_d and C_m) already in use; (d) the additional terms, if any, should not require additional empirical coefficients; and (e) the error (defined as the ratio of the rms values of the residue and of the measured force) should not exceed 10%. In this effort, the role of Re, Kc (or β) and the effects of three-dimensionality are to be investigated through additional experiments with other bluff bodies (rectangular cylinders and bluff flat plates) for the generalization and extension of the model equation to different geometries and dynamic response.

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WORK COMPLETED

An extensive review of the existing models has shown that the degree of empiricism increases with increasing Reynolds number and some measure of the unsteadiness of the motion (e.g., β). Some of these efforts, reaching to recent times, produced awkward expressions, applicable to a very narrow class of motions (Mei, 1994). This was due to the complexity of the problem rather than due to the lack of imagination of the model makers. The experimental studies of MOJS (1950) on forces on piles due to the action of progressive waves have provided a useful and somewhat heuristic approximation. Their model necessitated the introduction of a drag coefficient C_d and an inertia coefficient C_m in the expression for the in-line force. The MOJS equation does not deal with the transverse force. If F is the force per unit length experienced by a cylinder, then one has

$$F = \frac{1}{2}\rho C_d D|U|U + \rho C_m \frac{\pi D^2}{4}\frac{dU}{dt} \qquad (1)$$

where U and dU/dt represent the undisturbed velocity and the acceleration of the fluid. C_d and C_m are the Fourier-averaged drag and inertia coefficients, respectively. Clearly, the inertia and drag coefficients in the MOJS-model are forced to share the contributions of the vorticity field. Thus, the question naturally arises as to why one should not express the resistance in time dependent flows as a sum of the contributions of (a) the potential flow (with a precisely determinable inertia coefficient, unlike that in the MOJS equation) and (b) the concentrated or distributed vorticity shed during the entire history of the motion, expressed, if at all possible, in terms of a single vorticity-drag coefficient, dependent on the Reynolds number, Keulegan-Carpenter number, and the relative roughness. The experience of the past 50 years has shown that the MOJS equation still represents the best two-coefficient fit to the measured force. Even with the two experimentally-determined coefficients, its accuracy depends on Kc and β. In the so-called drag/inertia regime, it produces relatively poor results where the error may be as large as 50%. The addition of two more terms (a four-term Morison equation) through the introduction of two additional coefficients (dependent on Kc only), as proposed by Keulegan and Carpenter (1958) in their seminal work, does not always improve the predictions of the Morison equation. In fact, in many cases it makes them even worse! Furthermore, it is clear after 50 years of experience with Morison's equation that the fluid mechanics community is not interested with equations with four empirically-determined coefficients. In view of the foregoing, three new approaches have been pursued*:* A numerical analysis of the problem (Sarpkaya, et. al., 1997), based on the Favre-Averaged Navier-Stokes equations (FANS); calculation of forces from the measured vorticity distributions, and the development of a three-term model equation to replace the two-term model of Morison. It became clear that Direct Numerical Simulations (DNS), large Eddy Simulations (LES), and Reynolds- or Favre-averaged N. S. equations offer only a few data points, do not deal with industrially-significant problems, and do not provide real-time information for high-Reynolds-number flows. The force prediction from vorticity distribution, obtained through the use of the Particle Image Velocimetry (PIV), does not lead to a predictive model, only to the verification of the well-known integral expressions (Lighthill, 1986; Sarpkaya, 1998). Thus, we have pursued the last alternative: The development of a semi-empirical three-term model, valid for many bluff bodies in sinusoidally and non-sinusoidally oscillating flows. This proved to be very successful.

RESULTS

The additional analyses and numerical calculations reinforced the results of the previous year. Over 3,000 digital force-time-data files for cylinders and bluff plates have been evaluated in order to separate the resistance for each combination of (Kc, β, k_s/D) into the sum of an inviscid inertial force and a vorticity-induced force. Several fundamental concepts for the modeling of the ***vorticity-force*** have been examined. The first of these was the use of a steady-state drag (function of Re and k_s/D only) plus a history-integral force (dependent on Re, k_s/D, and β). Such a model was successful in the Stokes regime where the flow is unseparated. For separated flows, however, it did not turn out to be a meaningful approach because of the fact that the state of the steady flow (laminar or turbulent boundary layers) is dictated by circumstances significantly different from those in oscillating flows (wake return, etc.) Thus, it was not possible to define a consistent and conceptually satisfactory steady drag coefficient in the critical regime where the oscillating flow has already undergone full transition. The second was the use of a velocity-square-dependent drag force (as in the MOJS equation), an ideal inertial force (dependent on the theoretically-determined added mass coefficient), and a history term (dependent on the two coefficients just cited, including, of course, the parameters Kc, and β). This led to the re-writing of the MOJS equation as

$$F = -C_d|\cos\omega t|\cos\omega t + \frac{\pi^2}{Kc}C_m^* \sin\omega t - \frac{(C_m^* - C_m)\pi^2}{Kc}\sin\omega t \qquad (2)$$

and have shown clearly that the first two terms could not have provided a fit to the measured force better than that of MOJS. Here F is the normalized force and C_m is identical to the inertia coefficient C_m in the original MOJS equation and is obtained in exactly the same manner as before. Obviously, a third term is needed is to correct the residue resulting from the third and higher order harmonics. After considerable effort, a new and relatively simple three-term force model has been created.

$$F = -C_d|\cos\theta|\cos\theta + \frac{\pi^2}{Kc}C_m \sin\theta - \frac{\Lambda|\Lambda|}{C_d}\sin 3\theta \qquad (3)$$

in which

$$\Lambda = \frac{\pi^2}{Kc}(C_m^* - C_m) \qquad (4)$$

The new model is based largely on heuristic reasoning, mathematical simplicity, intuition, empirical correlations, constraints imposed by physical realizability, and experimental justification of the predictions. It has the following major characteristics: (a) it addresses to the most important shortcomings of the MOJS equation; (b) It applies equally well over all ranges of Kc, Re, and k/D (within the small body constraint); (c) it has distinct advantages over the MOJS equation; (d) It does not require additional empirical coefficients beyond those already in use (i.e., C_d, C_m, and, of course the lift coefficient); and (e) it may be extrapolated to more complex flow situations such as wave and current combination and non-sinusoidal motions (with some poetic license!).

Extensive calculations for all values of Kc, β, and k_s/D (previously encountered by this investigator) have shown that the new model predicts the measured force with an error less than 10% in all ranges of the governing parameters as described in detail by Sarpkaya (1998), (see, also, Figures 1-5 which show comparisons of the measured and calculated force traces for *sharp-edged bluff plates).* It may be concluded on the basis of our observations and measurements that the MOJS equation can be suitably modified through the use of a new parameter, defined by $(\Lambda|\Lambda|/C_d)$, with $\Lambda = \frac{\pi^2}{Kc}(C^*_m - C_m)$. It has been adopted here primarily for three reasons: Heuristic reasoning when applied to relevant conditions, mathematical simplicity, and the experimental justification of the model.

IMPACT/APPLICATIONS

The determination of resistance in time-dependent flows has been and will continue to be a scientific as well as applied research because of the fact that flows in nature are seldom steady and that there are an infinite number of unsteady flows. Thus, the reliable design of structures subjected to environmental loads is a monumental task. There is no question that the present work will give rise to similar models for other types of unsteady, quasi-steady, and transient flows and help to establish scientific links between the force acting on and the vorticity field created by a body. It is on this basis that one may eventually be able to resolve the more complicated problem of predicting the motion of a body on which a specified external force is applied. This will be particularly important for small smart vehicles operating in the ocean environment. Other alternatives (computer simulations and experiments) are prohibitively expensive and suffer from scale effects.

TRANSITIONS

The simplicity of the new model (only three terms with two previously used force coefficients, no additional computational or physical experiments, no vorticity measurements, at least for smooth and rough circular cylinders and bluff plates) is expected to lead to the general acceptance of the model for use in the design of offshore and naval structures and in the prediction of the dynamic response of bodies subjected to vortex-induced oscillations.

RELATED PROJECTS

It is related to our other efforts on LOCA and SRV loads on structures in pressure suppresion pools of nuclear reactors, Hydrodynamic Damping, Bilge Keels, and Flow Induced Oscillations. In addition, a number of substantive interactions have been established with NRC and other researchers in IFREMER (Brest, France) and Houston, TX.

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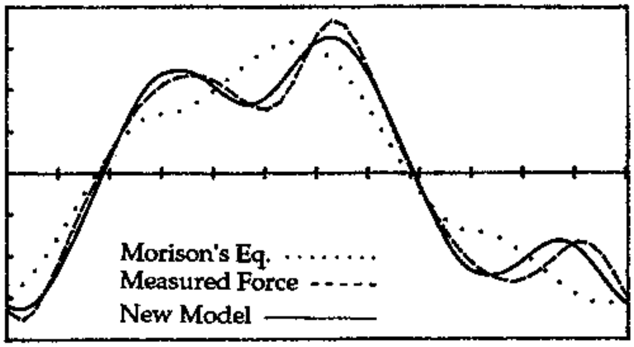

Fig. 1 Normalized force versus time for Kc = 11.7, Re = 55065, k/D = 0.0.

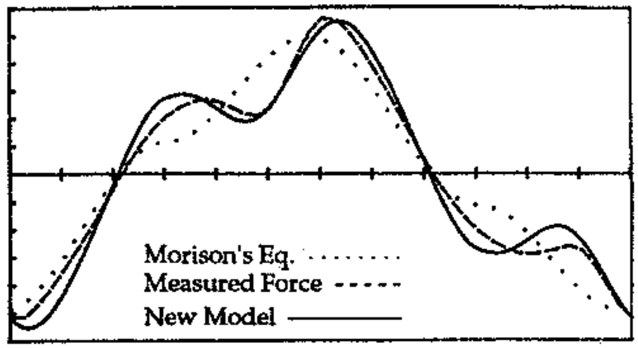

Fig. 4 Normalized force versus time for Kc = 10.9, Re = 71450, k/D = 1/50.

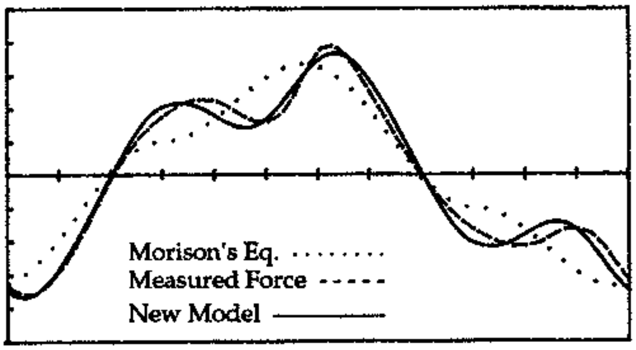

Fig. 2 Normalized force versus time for Kc = 12.9, Re = 43555, k/D = 0.0.

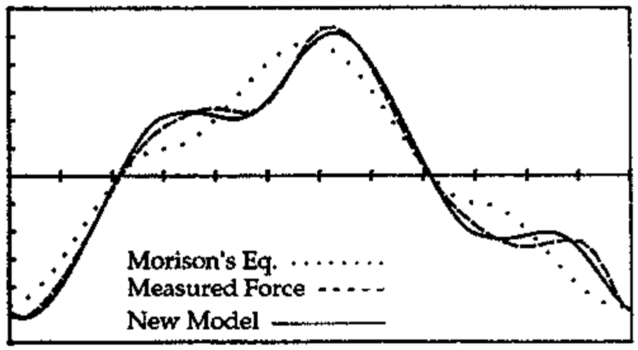

Fig. 5 Normalized force versus time for Kc = 12.7, Re = 62380, k/D = 1/50.

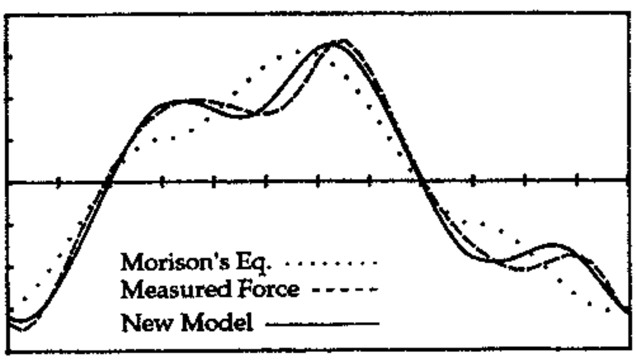

Fig. 3 Normalized force versus time for Kc = 14.0, Re = 47307, k/D = 0.0.

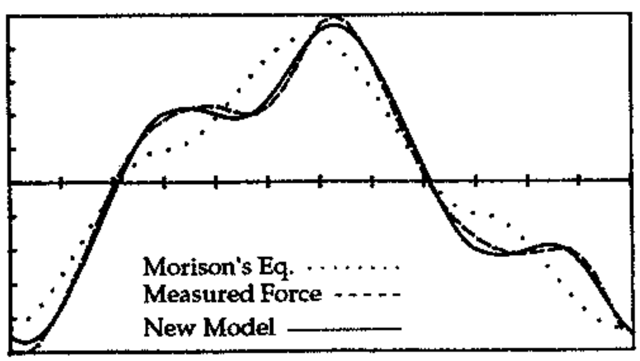

Fig. 6 Normalized force versus time for Kc = 13.0, Re = 64072, k/D = 1/50.