Proceedings of the Second International Pump Symposium

Sponsored by the

Turbomachinery Laboratories

Department of Mechanical Engineering

Texas A&M University

College Station, Texas

Dr. Dara Childs, P.E., Director

Dr. Jean C. Bailey, Editor

with assistance from

The Advisory Committee

and

The Staff of the Turbomachinery Laboratories

April 1985

FORCES ON CENTRIFUGAL PUMP IMPELLERS

by

Belgacem Jery

Graduate Student

Christopher E. Brennen

Professor

Thomas K. Caughey

Professor

and

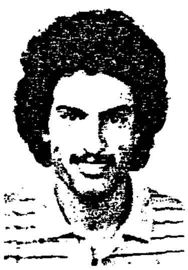
Allan Acosta

Professor

Division of Engineering and Applied Science

California Institute of Technology

Pasadena, California



Belgacem Jery is a Graduate Student at the California Institute of Technology in Pasadena, California. Mr. Jery holds an Engineer Diploma from ENSAM in Paris, France. His M.S. in Mechanical Engineering degree is from Caltech, Pasadena, California. Mr. Jery has conducted graduate research on rotor instability in high performance turbomachines as part of his Ph.D. work. He has published several papers on this subject. He is a member of ASME and Societe des Ingenieurs ENSAM.

Christopher E. Brennen is a Professor of Mechanical Engineering in the Division of Engineering and Applied Science, at the California Institute of Technology in Pasadena, California.

He holds B.A., M.A. and Ph.D. degrees in Engineering Science from Oxford University. Dr. Brennen was a Fulbright Scholar from 1969 to 1971. He has been honored by ASME, is a consultant and has many technical publications.

Thomas K. Caughey is a Professor of Applied Mechanics at the California Institute of Technology in Pasadena, California.

He received B.Sc. and M.E. degrees from Glasgow University in 1948, an M.M.E. degree from Cornell University in 1952 and a Ph.D. degree in Engineering Science from California Institute of Technology in 1954.

Dr. Caughey's fields of interest are Applied Mathematics, Dynamics, Vibrations, Acoustics, Stability, Non-linear Systems, Stochastic Processes, Chaos and Control Theory.

Allan J. Acosta, Professor of Mechanical Engineering at the California Institute of Technology since 1954, is currently involved in the study of internal flows in hydraulic machinery and fluid-structure interactions in these machines. He has also studied cavitation effects in hydraulic machinery and cavitation inception as it occurs in applications of naval hydrodynamics.

Prior to joining Caltech, he worked on model pumps for the Grand Coulee Irrigation Project. In 1954, he joined Caltech's Hydrodynamics Research Laboratory and worked on problems in centrifugal pump impellers, axial flow pumps and inducers and cavitating hydrofoils.

A Fellow of ASME, Dr. Acosta is a two-time recipient of the Knapp Award, and received the Moody Award, the 1975 ASME Melville Medal, and the Henry R. Worthington award in 1982. He has been chairman of the Ocean Engineering Division (1967) and the Fluids Engineering Division (1980).

A registered professional engineer in the State of California, he is also a member of the International Association of Hydraulic Research, the American Association for the Advancement of Science, the Society of Naval Architects and Marine Engineers and Sigma Xi.

ABSTRACT

Forces are exerted on a centrifugal pump impeller, due to the asymmetry of the flow caused by the volute or diffuser, and to the motion of the center of the impeller whenever the shaft whirls. Recent work in the measurement of these forces, as a function of the whirl speed to shaft speed ratio, and the influence of the volute, is reviewed. These forces may be decomposed into a steady force, a static stiffness matrix, a damping matrix and an inertia matrix. It is shown that for centrifugal pumps of the moderate specific speed typical of boiler feed stages, there is a region of potential shaft vibration excitation from the hydrodynamic forces if the operating speed is well above the first flexural critical speed.

INTRODUCTION

The need for more powerful, more efficient and more reliable turbomachines has grown substantially in the past decade. As a result, a great deal of effort is being devoted to solving increasingly complex design and manufacturing problems. One such problem is a self-excited rotor vibration phenomenon widely known now as rotor whirl. The research work described herein is an experimental investigation of rotor whirl related instabilities in centrifugal flow pumps. This investigation is part of an on-going program that started in 1977 at the California Institute of Technology, under the sponsorship of NASA, in conjunction with the development of the Space Shuttle Main Engine (SSME). A recent article by Ehric and Childs [1] provides excellent background information on the subject of rotor whirl in general. As far as the present research is concerned, detailed descriptions of the test program, the experimental setup and the preliminary findings of the investigation exist elsewhere in the literature [2,3,4,5,6,7]. References [4] and [7] are especially recommended. Contributions from other sources are also noted in the literature [8,9,10,11,12,13,14]. More recent experimental test results are reported herein. A discussion is provided of the measured hydrodynamic stiffness, damping and inertia coefficients and their relation to the various impeller and volute or diffuser ~~geometries and~~ to the wide range of flow conditions. Finally, an example which illustrates the practical use of these rotordynamic coefficients is provided.

EXPERIMENTAL OBJECTIVE

When introducing a new turbomachine design, engineers generally agree that model testing is the only sure way to predict the dynamic behavior, especially for operation off-design. If done for every new product, this can prove to be very costly. However, the lack of theoretical data leaves very little choice to the designer. Empiricism, intuition, and past practical experience are usually brought into play. Another alternative is to conduct a limited, but very carefully selected, set of experiments, in which key parameters are varied and tested in a systematic fashion. Results of such tests can be extended to a much larger class of machines and operating conditions, by the use of simple scaling (similarity) laws. This was the approach chosen in the current experimental work. The objective herein is to provide designers of centrifugal flow pumps with a deeper understanding of the role of hydrodynamic impeller-volute diffuser interactions in the excitation or damping of rotor whirl. From a rotordynamics point of view, this means providing impeller-volute diffuser hydrodynamic stiffness, damping and inertia coefficients to be used in determining the critical speeds and the Onset Speed of Instability (OSI).

EXPERIMENTAL PROCEDURE

To measure these rotordynamic coefficients, it was decided to perform what amounts to a set of *forced vibration* tests. The rotor of a centrifugal pump is forced into a whirling motion in which the impeller center is made to follow a circular orbit, at a constant angular rate Ω, while the impeller axis remains parallel to the pump centerline. This takes place in addition to and independently of the normal impeller rotation at the constant angular rate ω. The whirl orbit center coincides with the volute or diffuser geometric center 0 (Figure 1). The orbit radius ϵ is constant and its value of 1.3 mm was carefully chosen: too large an ϵ would void the assumption of small perturbations: too small an ϵ would result in forces not large enough to be measured accurately. The word "forces" here refers to the components of the generalized hydrodynamic force vector {F} acting on the impeller as it undergoes simultaneous whirl and rotation.

All six components of {F} are sensed by a rotating dynamometer, strategically placed between the impeller and the drive shaft to avoid any drive system noise and unwanted forces. By design, both the shaft and the dynamometer could be considered infinitely rigid for the purpose of these measurements. Since whirl is usually associated with the lateral deflection of the rotor, only two of vector {F} components will be discussed, namely, the two lateral hydrodynamic forces F_x and F_y acting at the impeller center, in a plane perpendicular to the machine axis of rotation. Referring to Figure 1, these forces can be written in the form:

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = \begin{Bmatrix} F_{ox} \\ F_{oy} \end{Bmatrix} + [A] \begin{Bmatrix} x \\ y \end{Bmatrix} \quad (1)$$

where x and y represent the coordinates of the impeller center measured from the center of the volute 0. In both this equation and all the equations and results which follow, dimensionless quantities are used. The linear form of equation (1) assumes small offsets x and y as allowed by the choice of ϵ. At the present time little is known of the possible non-linear effects.

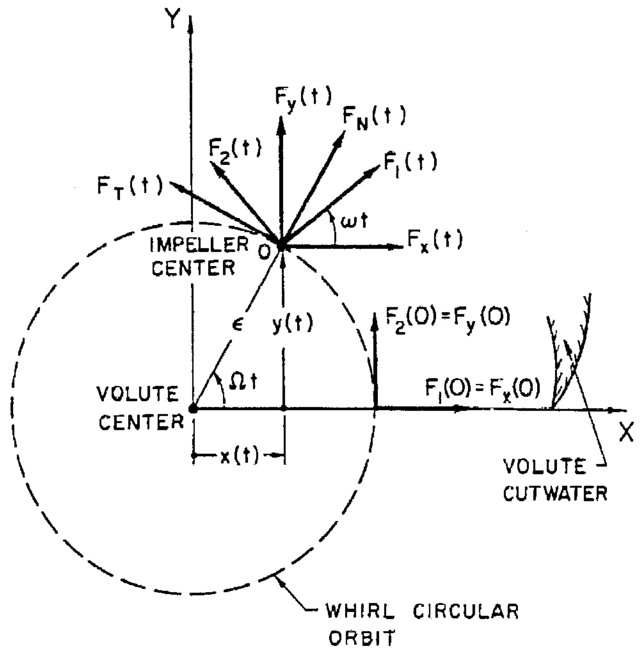


Figure 1. Schematic Diagram Representing the Lateral Forces in the Rotating Dynamometer Frame (F_1,F_2), in the Stationary Volute Frame (F_x,F_y) and in the Local Polar Coordinate Frame (F_N,F_T).

When x and y are *fixed* in time, F_x and F_y represent the *steady* lateral forces, and can be viewed as the sum of two forces: a fixed force (F_{ox} and F_{oy} would be only forces present, should the impeller center coincide with the volute center, i.e., $x=y=0$) and a quantity proportional to the displacement, which represents a static fluid "stiffness" effect. These two quantities have been the subject of previous reports [3,4,5,6]. Herein, the analysis and experiments for the case of non-zero whirl velocity, in which x and y are harmonic functions of time, ($x=x(t)=\epsilon \cos \Omega t \cdot r_2$, $y=y(t)=\epsilon \sin \Omega t \cdot r_2$), will be discussed. Damping and inertia effects are associated with the harmonic velocities and accelerations $\dot{x}$, $\dot{y}$, $\ddot{x}$, $\ddot{y}$ of the impeller center. In this case, equation (1) can be generalized to the form: