"AUTO-OSCILLATION OF CAVITATING INDUCERS"

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AUTO-OSCILLATION OF CAVITATING INDUCERS

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ABSTRACT

This paper presents details of measurements on the instability known as auto-oscillation which occurs in systems with cavitating pumps. Specific measurements are made of onset cavitation number and auto-oscillation frequency for a range of inducers. It has been shown that auto-oscillation is a system instability caused by the active dynamic characteristics of the cavitating pump.

A system analysis is presented which utilizes previously measured dynamic transfer functions for the inducers; the resulting predictions of instability are consistent with the observations. Though the onset cavitation number is a function of the entire system it is also shown that, given the onset cavitation number, the auto-oscillation frequency is only weakly dependent on the system and primarily a function of the pump dynamics.

Detailed measurements of the amplitude and phase of fluctuating pressures and flow rates during auto-oscillation are also presented. These strongly suggest that the pump dynamics are primarily determined by the complicated flow at inlet to the inducer which involves pre-swirl generated by a strong backflow. Some data on the non-linear effect of auto-oscillation on overall mean performance are also presented.

Nomenclature

A	Inducer inlet area
a_{ijk}	Polynomial coefficients for transfer function jets
C	Air bladder compliance
ΔE	Fluctuating energy drain of system
Δe	$\Delta E/\|\tilde{h}_1\|^2$
H	Blade tip spacing = circumference/number of blades
$\bar{h}$	Mean total head
$\tilde{h}$	Fluctuating total head
I_u, I_D	System impedances upstream and downstream of pump
$\bar{m}$	Mean mass flow rate
$\tilde{m}$	Fluctuating mass flow rate
[S]	System transfer function
[T]	Transfer function
U_T	Impeller tip speed
[Z]	Pump transfer function
φ	Flow coefficient = Pump Flow Rate/AU_T
ψ	Head coefficient = Head rise across pump/ρU_T^2
σ	Cavitation number = Net positive suction pressure/ $\frac{1}{2}\rho U_T^2$
ρ	Liquid density
Ω	Radian frequency
ω	Reduced frequency = $\Omega H/U_T$
ω_N	Natural reduced frequency
[I]	Identity matrix

1. INTRODUCTION

The phenomenon of auto-oscillation or surge has often been encountered with cavitating pumps (for example Refs. [1] to [14]). It represents one of the commonest instabilities derived from two phase flow which are encountered in hydraulic systems. It can be quite deleterious to the operation, performance, control and lifetime of a pump.

In this paper we present an account of experimental investigation of auto-oscillation in cavitating inducers and attempt to correlate these observations with a model for hydraulic system analysis based on recent improvements in the state of knowledge of the unsteady, dynamic characteristics of cavitating pumps (for more detail see [15]). We shall concentrate on auto-oscillation and make only passing reference to the less severe instabilities such as rotating cavitation and alternate blade cavitation [3,4,6,7] which can sometimes occur in inducers. These are probably less troublesome because they are local flow oscillations in which the rest of the hydraulic system does not usually become excited. Furthermore, we shall not consider the added complications which arise when the inlet and discharge lines become sufficiently long for acoustic resonance frequencies in these lines to be excited by blade passage frequencies [16]. Such phenomena could however be accommodated by the inclusion of compressible pipe flow transfer functions (see Ref. [17]) in the stability analysis rather than the incompressible models used in Section 7. Finally, we shall consider only hydraulic systems which are fixed in some non-inertial coordinate system. The methodology could clearly be expanded for the analysis of accelerating systems such as occur in the POGO instability in liquid propelled rockets [18,19,20]. However, this requires a stipulation of the interaction between the global acceleration of the unsteady flow rate relative to the system which is beyond the scope of the present paper.

Auto-oscillation is a function of the entire hydraulic system of which the cavitating pump may be only a small part. It has been recognized [1,5,7,12, 13,14] that the system influences the onset and amplitude (and perhaps the frequency) of the oscillation but that the cavitation in the pump is the source of the problem. There exists a number of speculations [3,4,6,10,13,14] on the precise mechanism through which the cavitation excites and sustains the instability but none are proven. Both Barr [4] and Etter [6] suggest that it is associated with an inherent instability in the cavity length when this is close to the blade passage length [4] or when the cavity on one blade collapses at the entrance to the next blade passage [6]. Badowski [3] has proposed an instability in the coupling between the cavitation, the head production and the backflow induced prerotation. Both Sack and Nottage [13] and Young, Murphy and Reddecliff [14] have attempted to factor in system effects though their analyses are limited by lack of information on the dynamic characteristics of cavitating inducers. The recent availability of dynamic transfer functions for cavitating inducers [21,11,12,22,23,24] has permitted a more accurate evaluation of such system effects.

Finally, we should comment on the evident analogy between auto-oscillation and the surge phenomena which occurs in compressors [25,26]. (We note in passing that rotating cavitating and rotating stall also appear to be superficially analogous.) The major difference is that the cavitating pump instabilities can occur at operating points where the slope of the head rise versus flow rate curve is negative. On the other hand, Greitzer [25] has indicated that a positive slope is necessary for the compressor instabilities. In the case of surge he concisely describes the need for a minimum positive slope in order to provide a source of fluctuating energy sufficient to overcome the dissipation in other parts of the system. The analysis of Section 7 similarly defines such a minimum for pumps in the absence of cavitation.

Similar instabilities in regions of positive head rise/flow rate slope can occur with cavitating or non-cavitating pumps [27]. However, auto-oscillating usually occurs in regions of negative slope when the extent of cavitation has reached some critical value. Therefore, it is evident that cavitation has the potential of providing some other source of fluctuating energy different from that in the compressor problem. *Indeed cavitation-induced* auto-oscillation occurs when the system is apparently stable according to the kind of <u>quasi-static</u> analysis used in the compressor problem. In the present paper we attempt to demonstrate that auto-oscillation is due to the dynamic rather than the quasi-static characteristics of the cavitating pumps. We feel that similar attention should be paid to the dynamic as opposed to the quasi-static behavior of compressors. Indeed Ng and Brennen [12] found that the characteristics deviated substantially from quasi-static values for reduced frequencies based on tip speed and circumferential blade spacing as low as 0.1.

2. EXPERIMENTAL FACILITY

The experimental investigation of auto-oscillation was performed in the Dynamic Pump Test Facility (DPTF) at the California Institute of Technology; a schematic of this facility which is described elsewhere [11,12,15] appears as Fig. 1. Instrumentation utilized in the experiments include (i) two laser

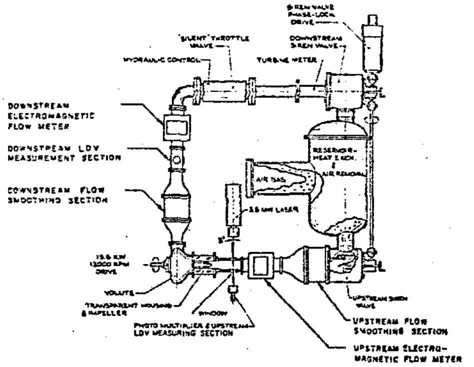

Fig. 1 Schematic plan view of the Dynamic Pump Test Facility used in present experiments.

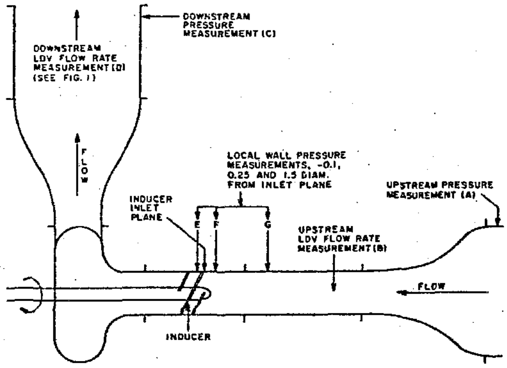

Fig.2 Schematic showing pressure and flow rate measurement locations. Transducers were also placed at various circumferential locations at the points E and F. Letters are used for presentation of results in Fig. 7,8 and 9.

doppler velocimeters for measurement of the unsteady flow rate at inlet to and discharge from the pump (ii) two strain gauge pressure transducers for measurement *of the total head fluctuations of the inlet and dis*charge flows (iii) variable reluctance transducers mounted on the wall of the duct in the neighborhood of the inlet to the transducer so as to determine the axial and circumferential variations in fluctuating pressure in this region (axial locations are indicated in Fig. 2). All of this dynamic data was recorded simultaneously on a 14-channel Ampex tape recorder and processed using a Spectral Dynamics signal analyzer in order to obtain spectra and cross-correlations. Additional instrumentation included a turbine flow meter and a magnet proximity transducer to monitor the rotational speed.

Experiments were performed using five different inducer/impellers. Impellers 4 and 6 *were 7.6cm. and* 10.26cm. diameter models of the low pressure oxygen pump rotors in the Space Shuttle main engine [12]. Impellers 5 and 7 are geometrically similar 7.6cm. and 10.26cm. diameter three-bladed helical impellers with swept leading edges, zero blade cant and 9° blade angle [1]. Impeller 8 was 10.26 cm.diameter four-bladed helical inducer with a zero blade cant, swept