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CONTRACT NAS 8-28046

DYNAMICS OF CAVITATING CASCADES

FINAL REPORT

PREPARED BY
A. J. ACOSTA, C. BRENNEN AND J. H. KIM

FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER, NASA
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

DIVISION OF ENGINEERING AND APPLIED SCIENCE
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

REPORT NO. E-184.1
NOVEMBER 15, 1972

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Dynamics of Cavitating Cascades

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Engineering and Applied Science Division

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Pasadena, California 91109

Report No. E-184.1
November 15, 1972

1. Introduction. The importance of the POGO instability in the operation of liquid rocket engines and the role played by the cavitating turbopumps in that instability has focused renewed attention in means of analyzing and describing these unsteady flows. The instability itself and the coupling between the pump and associated structure are described in references (1, 2). An important feature in this coupling is the characterization of the turbopump performance when subject to the unsteady pressure and mass oscillations in the feed and discharge lines. Indeed, even without the complications introduced by cavitation this is a nearly unexplored subject.

The presence of cavitation greatly complicates the flow within the pump even in the absence of imposed unsteady perturbations. It may appear in a number of forms[3, 4, 5] in an axial inducer - a typical feature of most turbopumps. Roughly these may be classified as "bubble" cavitation in which free stream nuclei grow within low pressure regions near the pump blades; "blade" cavitation in which a vaporous cavity or wake becomes attached to the low pressure side of the blade; and of special interest in turbopumps "backflow" cavitation arising from the vortices shed in the tip clearance flow. The cavitation occurring within these tip clearance flows may occur as growing bubbles or as a vortex core similar to that observed trailing behind propellers. All three processes may occur concurrently on a given fluid and inducer or with various circumstances one type only may predominate. In any case in whatever form the cavitation occurs, it is very desirable to develop means of understanding <u>unsteady</u> cavitation flows for the light that may be shed on the POGO instability and for the interpretation of unsteady cavitating turbopump tests.

In the present work attention is focused on only one of the types of cavitation mentioned, namely "blade" cavitation, or as it is sometimes called "surface" cavitation. This type of cavitation occurs frequently on hydrofoils and inducer pumps operating in cold water. Analyses of blade cavitation carried out with the help of a potential flow cascade model affords reasonable estimates of losses induced by cavitation[6] on inducers in steady flow. It seems reasonable and appropriate therefore to undertake extentions of this useful flow model to unsteady flows of the type that can arise in turbopump applications such as the POGO instability mentioned.

2. Background. In addition to the normal steady pump characteristics used in the analysis of system instabilities an additional parameter, the "cavitation compliance"[2, 3] defined by the relation

$$C_B = -\rho_L \, \partial V_c / \partial p_\infty \qquad (1)$$

plays an important role in relating the response of a cavitating pump to oscillatory flows. In this, ρ_L is the liquid density, V_c, the volume of vapor or gas cavities and p_∞ is the suction pressure. This quantity gives the difference of in-and-out flows in respect to the fluctuating pressure causing the cavitation. In general it should be expected to be a function of frequency and perhaps complex (in the time variable) although field data recently surveyed[7] are not consistent enough to permit deductions on these points. In accordance with the above definition, all forms of cavitation mentioned may be expected to contribute to the cavity volume and therefore to contribute to the "compliance" term.

In the present work the contribution to the compliance of the blade surface cavitation will be considered. This work is divided into two subdivisions; (a) the estimation of compliance with a quasi-steady theory, and (b) the development of an appropriate unsteady cavitating flow theory. The basic idealization in both approaches is the adoption of a two-dimensional cascade flow model to represent radial sections of the flow within an inducer. The other assumptions necessary to effect progress are those of incompressible potential flow and thin wing theory. Even with these simplifications formidable tasks of analysis remain. It is possible, however, to carry through to a satisfactory conclusion the quasi-static calculation of compliance and to present the results of comparisons with field data. Considerable progress has been made on the full unsteady problem to the point of exhibiting the formal solution although numerical work has not been done. A simpler and related problem of a cavitating channel flow is discussed together with numerical results for a pulsating jet.

These works have been incorporated in papers listed in Publications. In what follows, the principal results of these publications are briefly discussed together with the conclusions that can be drawn. The analytical approach used in both the quasi-static and dynamic analyses is outlined in appendices with key formulae.

3. Results. It should perhaps first be mentioned that both theories employ fully linearized free streamline theory. Such theories permit first order estimates to be made of relevant flow quantities provided that the disturbance superposed on a uniform flow by the cascade sections

are "small". This means necessarily that angles of attack, cavitation numbers, blade thickness etc., are all small and, of course, it is assumed that the true three dimensional flow is such that the cascade approximation is a useful one. These restrictions together with the obligatory reservation as to real fluid effects mean that the results to be discussed can only reveal trends and are perhaps only of a qualitative although useful value.

Quasi-static Analysis. As described in publications (1, 2) radial sections of an axial inducer are developed onto a cascade plane. The flow approaches the vanes of the cascade with angle of attack α and cavitation number $\sigma = (p_s - p_c)/\rho V_1^2/2$, ρ being the liquid density, V_1 the relative velocity for upstream, p_s the static pressure there and p_c is the cavity pressure. The vane system is characterized by a vane thickness/normal vane spacing, d. (In most previous cascade theories, blade thickness is assumed to be zero). A free streamline springs from the nose of the vane section and terminates some distance downstream of the leading edge depending on angle of attack, cavitation numbers and vane geometry. When the cavity becomes infinitely long it is said to be "choked" and the corresponding cavitation number as the choking cavitation number.

The free streamline encloses a certain area or volume/unit depth of cascade. Numerical integrations were performed to determine this volume, V^*, for various values of cascade geometry and cavitation numbers. This volume is scaled with the square of the local vane spacing and it was then readily possible to compute a dimensionless compliance

$$K^* = -\frac{1}{h^2}\frac{\partial V^*}{\partial \sigma} \qquad (2)$$

where h^2 is the vane spacing. The value of K^* at the vane tip may be shown to be related to the dimensional compliance C_B by

$$K_T^* = \frac{V_T^2}{2HA_i} C_B \qquad (2')$$

A_i being the inducer face area, V_T the relative velocity at the vane tip and H the spacing there. The salient points emerging from this analysis are

(i) the cavitation number σ_c at which the flow is choked (cavitation breakdown) increases with foil thickness, (This is important in correlating breakdown performances).

(ii) the compliance tends to infinity as $\sigma \rightarrow \sigma_c$

(iii) the compliance tends to zero as σ becomes large.

The results of this analysis were then extensively compared with field data as available. It may be said that breakdown cavitation numbers agreed fairly well with water test data being pessimistic by 0.002 in σ_c at the worst location on the J-2 oxidizer pump. But of much more significant interest is the comparison of theoretically derived compliance values with test data for J-2 fuel, H1 fuel, F1 fuel and H1 oxidizer pumps. The overall result is that quasi-static compliances so derived are from one to two orders of magnitude too low. It is cautioned that the experimental values of C_B are not consistently determined and even exhibit scatter of one order of magnitude. Nevertheless it appears likely that blade surface cavitation provides volume changes with pressure that are too small as determined by a quasi-static approach.

Dynamic Cascade Analysis. The basic point of view is the same as the previous static calculation except that the approaching and leaving flow velocities up-and-downstream of the cascade are oscillating. More specifically, only the component of flow normal to the cascade axis has a disturbance (this corresponds to an axial velocity perturbation). In general, the up-and-downstream velocity perturbations may be different in amplitude and phase. The blade surface cavity volume changes with time in such a way that continuity is satisfied. At the same time the surface of the cavity grows dynamically under the imposed velocity disturbances. It is not now a streamline but a material surface. The complexities introduced by this fact are circumvented by the assumptions of the linear analysis and the over-riding desire to extract only the least information required for the purpose of dynamic analysis. An example of this type of problem of an unsteady cavity flow is given in Publication 3. In this work the unsteady flow past a base-cavitating slender wedge in a channel of finite height is treated. The wedge is stationary but the velocity in the channels up-and-downstream fluctuate and there is a corresponding fluctuation of the cavity boundary and volume — just as for the cascade situation. It is possible to formulate and carry out an analysis of this type of motion for infinitesimal fluctuations around an average steady state flow (as is done in Publication 3). With these results, details of the velocity distribution and so forth can be calculated. This may be of interest in some applications but in the present framework only the overall effect of inserting the cavity-body system into the channel need be determined.

The flow up-and-downstream in the channel has fluctuating velocity components, $\hat{u}_1$, $\hat{u}_2$ say. In the absence of the body-cavity system elementary dynamic principles may be used to calculate differences in fluctuating pressure between any two remote points in the channel. The primary effect of inserting the body-cavity system (which participates dynamically with the flow) is to alter the pressure by amounts $\hat{p}_1$, $\hat{p}_2$ at these remote points for the given velocity disturbances. The magnitude of the effect depends on flow geometry, frequency and so on. As a general remark then insofar as dynamics of unsteady cavitating internal flows are considered, we wish to relate the four complex, frequency dependent quantities, $\hat{u}_1$, $\hat{u}_2$, $\hat{p}_1$, $\hat{p}_2$. The use of linear theory in this type of calculation has been stressed. It follows naturally then that these four quantities are similarly related, e.g.,

$$(\hat{p}_2, \hat{u}_2) = T(\hat{p}_1, \hat{u}_1) \tag{3}$$

where T may be thought of as a 2×2 complex transfer matrix having eight component coefficients; these are independent of $\hat{p}_1$, $\hat{u}_1$, etc., but are frequency dependent and of course depend on the basic flow geometry.

In Publication 3 discussed before, it was possible to formulate the unsteady solution so that the components of T could in principle be calculated. This was only done however for a special limiting case, the pulsating channel flow terminating in an infinite reservoir at constant pressure. This case is not without interest even though T becomes degenerate and the relation

$$\hat{p}_1 = \rho U \hat{u}_1 R$$

is obtained where ρ is the liquid density, U the mean channel speed and $R = R(\frac{\omega h}{U})$, ω being angular frequency and h the channel semi-height. R is calculated in detail and is shown to be complex and its modulus is less than unity for practical values of the reduced frequency $\omega h/U$.

Similar but much more complicated relations would result for finite cavities. The interest in the above result lies in the observation that there is a dynamic reaction (similar to a compliance) even for the simplest choked flow, that it is strongly frequency dependent and exhibits complex values. It should be noted that the quasi-static approach previously discussed cannot provide this type of information.

The analysis of cascade flows is in principle no more difficult than the channel flow; indeed, the mathematical formalism is essentially the same. The basic steps of this calculation are summarized in Appendix I. There it may be seen that the theory is completely formulated for an inducer cascade of flat plates of arbitrary stagger angle and cavity length. Also the approach necessary to calculate the elements of the transfer matrix T is indicated. This calculation, however, is very involved and there was insufficient time available to produce numerical results. As a consequence it is not yet possible to make an assessment of the importance of dynamic effects on blade surface cavitation compliance and to determine thereby if the large discrepancy revealed by the quasi-static analysis is resolved.

4. Conclusions. A steady cavitating flow theory has been used to evaluate breakdown cavitation numbers in inducer cascades and the cavitation compliance. The cavitation breakdown limit is significantly increased by blade thickness ratios in practical use and, near breakdown, the cavitation compliance is also increased. By comparison with field data it is concluded that blade surface cavitation as determined by a steady cavitation flow theory is far too small.

A fully linearized non-steady cavity flow theory for the flow through flat plate is formulated and a formal solution for the compliance is obtained. No numerical results were, however, obtained. By inspection of the solution it can be determined that unlike the quasi-static value the compliance is now complex and frequency dependent. Numerical estimates of the dynamic effect need to be made before the importance of blade surface compliance can be established.

Appendix I. Linearized theory of unsteady flow past a cavitating inducer cascade.

A sketch of the flow is given in Figure 1. The steady angle of incidence α, is supposed small; the cavity is assumed to be slender so that only small velocity disturbances (u, v) in the (x, y) directions respectively result. Far upstream the component of velocity normal to cascade has perturbation $\hat{N}_1 e^{j\omega t}$; the tangential velocity component T_1 remains fixed so that there is only an axial velocity fluctuation approaching the inducer. Far downstream (not shown) the flow must be parallel to the vanes or x axis; because of this the normal N_2 and tangential T_2 fluctuations are coupled.

The problem is to determine the residuary pressures $\hat{p}_1, \hat{p}_2$ far up-and-downstream given the steady (or average) angle of attack α_1, average cavitation number σ, stagger angle γ, spacing d and the fluctuating normal components $\hat{N}_1, \hat{N}_2$. It is assumed that the whole system is fluctuating at a single frequency ω so that the time representation of $\hat{N}_1$ is $\hat{N}_1 e^{j\omega t}$ etc., where the coefficients $\hat{N}_1, \hat{N}_2, \hat{p}_1$, etc., can be complex in the time variable.

Very briefly the method of approach is to assume that (u, v) are velocity components of an incompressible potential flow; the combination $w = u - iv$ is an analytic function of z with boundary conditions

i) (u_1, v_1) specified far upstream
ii) (u_2, v_2) specified far downstream
iii) $v = 0$ on the wetted surface
iv) $p = p_c$ = const. on the cavity boundary.

Equations (i), (ii) incorporate both the average (steady) and fluctuating values.

A solution is effected by appeal to the smallness of (u, v) relative to the approach velocity so that via the linearized Euler equation of motion the pressure condition (iv) becomes

$$\text{(v)}\quad u_c = u_{cs} + \hat{g}\, e^{j\omega(t - x/U_1)}$$

where u_{cs} is the perturbed value for the steady flow and $\hat{g}$ is a constant to to be found. Condition (v) is to be applied on the x-axis as in other linear theories. The stage is set to determine the function w(z); this is done by transforming the z-plane into the upper half ζ-plane by the relation

$$z = \frac{d}{2\pi}\left\{e^{-i\gamma}\ell n\,(1 - \zeta/\zeta_1) - e^{i\gamma}\ell n\,(1 - \zeta/\overline{\zeta}_1)\right\} \qquad \text{(A-1)}$$

where

$$\zeta_1 = \sqrt{d}\; e^{i(\pi/2 - \gamma)}$$

which collapses all of the blades onto the real axis of the ζ-plane with the correspondence and boundary conditions shown in Figure 2. The resulting solution is of the form

$$w(\zeta) = w_{cs}(\zeta) + \hat{w}(\zeta)e^{j\omega t} \qquad \text{(A-2)}$$

where subscript (cs) denotes the steady solution already completely determined in publications (1, 2). The length ℓ of the cavity is thereby determined and only the solution for the fluctuating part $\hat{w}(\zeta)$ remains to be found. Following standard methods this solution is

$$\hat{w}(\zeta) = \frac{\hat{g}}{\pi\sqrt{\zeta(\zeta - S)}}\int_0^S \sqrt{\xi(S-\xi)}\, d\xi\, \frac{e^{-jkx(\xi)}}{\xi - \zeta} + \frac{A\zeta + B}{\sqrt{\zeta(\zeta - S)}} \qquad \text{(A-3)}$$

in which S is the transformed length of the steady cavity. The conditions at up and downstream infinity completely and uniquely determine constants A, B, $\hat{g}$ so that the unsteady solution is found.

We now indicate how the residuary pressures $\hat{p}_1, \hat{p}_2$ can be obtained to determine the components of T(Eqn. 3). The Euler equation of motion (following Publication 3), i. e.,

$$\frac{\partial u}{\partial t} + U_1 \frac{\partial u}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

is integrated by parts after the substitution $u = \hat{u}\, e^{j\omega t}$ etc., so that the pressure gradient due to the "solid" body oscillation $j\omega \hat{u}_1 e^{j\omega t}$ can be removed. This results in the equations

$$U_1 \left\{\sqrt{1+\sigma}\,\hat{g} - \hat{N}_1 \cos\gamma\right\} - j\omega \int_{-\infty}^{0} x\, \frac{d\,\hat{u}(x, 0^+)}{dx}\, dx = +\frac{1}{\rho}(\hat{p}_1 - \hat{p}_c) \qquad \text{(A-4)}$$

and

$$U_1 \left\{(1-\alpha_1 \tan\gamma)(\cos\gamma + \tan\gamma)\hat{N}_2 - \hat{N}_1 \cos\gamma\right\} - j\omega \int_{-\infty}^{0} x\, dx \frac{d}{dx}\hat{u}(x, 0^+) = \frac{1}{\rho}(\hat{p}_1 - \hat{p}_2) \qquad \text{(A-5)}$$

where now

$$\sigma = \frac{p_{-\infty} - p_c}{\rho\, U_1^2/2}$$

is the cavitation number based on the average pressure far upstream.

Equations (1-5) provide a formal solution for the unsteady problem. The infinite integrals of Eqns. A-4, 5 do require great care in evaluation, however, because they are double integrals with rapidly oscillating integrands. These integrals are best evaluated in the transform (ζ) plane as was done for the simpler problem treated in publication (3). As in that work the integrands are all integrable but exhibit weak singularities at certain points.

5. Publications.

(1) "A Note on Turbopump Blade Cavitation Compliance for the POGO Instability", by C. Brennen and A. J. Acosta, ASME Polyphase Flow Forum, San Francisco, March 1972.

(2) "Theoretical Quasistatic Analyses of Cavitation Compliance in Turbopumps", by C. Brennen and A. J. Acosta, to appear in Journal Spacecraft and Rockets.

(3) "A Note on the Unsteady Cavity Flow in a Tunnel", by J. H. Kim and A. J. Acosta, submitted for publication, American Soc. Mech. Engineers.

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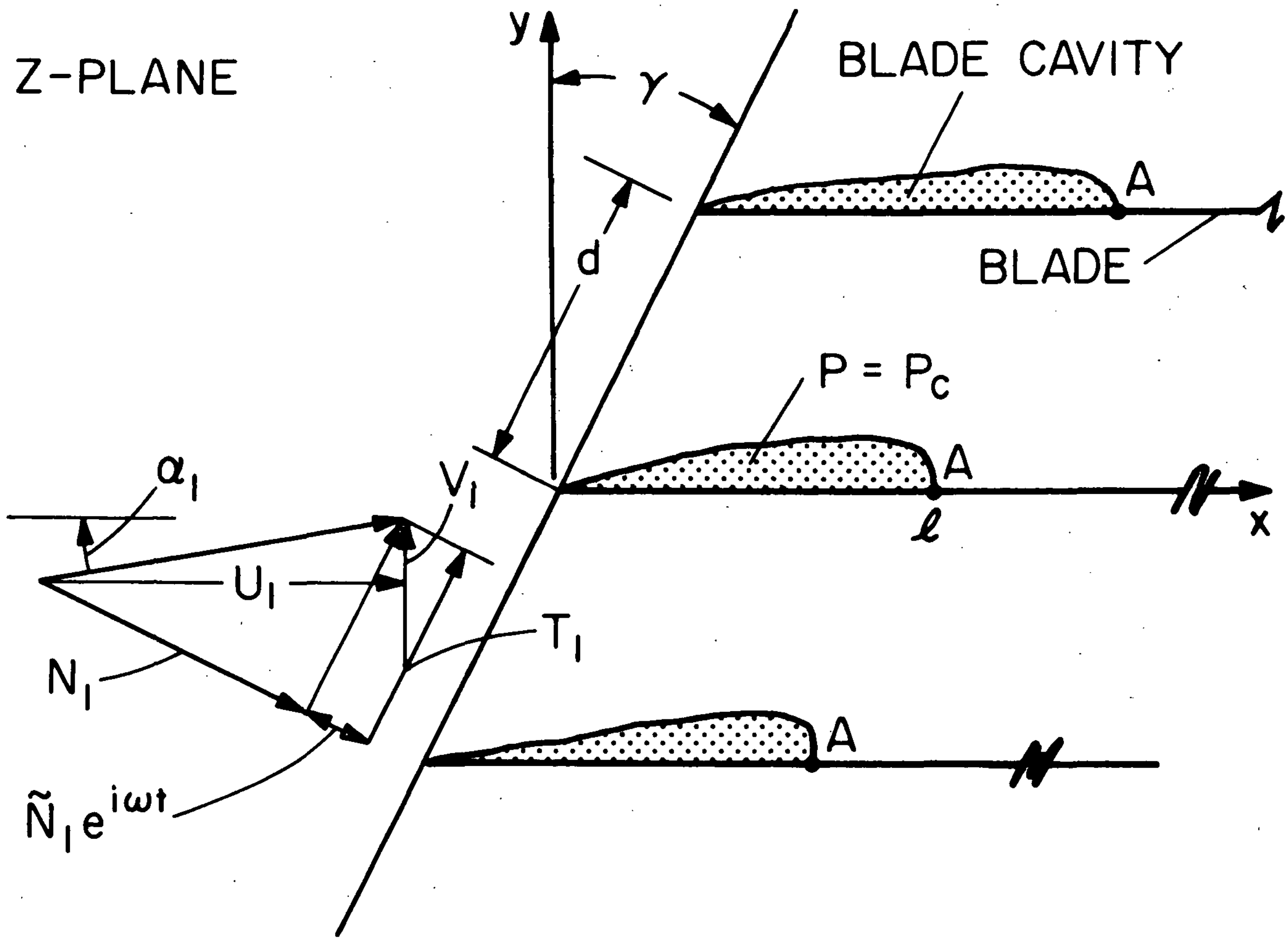

Figure 1. Sketch of Cavitating Cascade Showing Fluctuating Upstream Velocities.

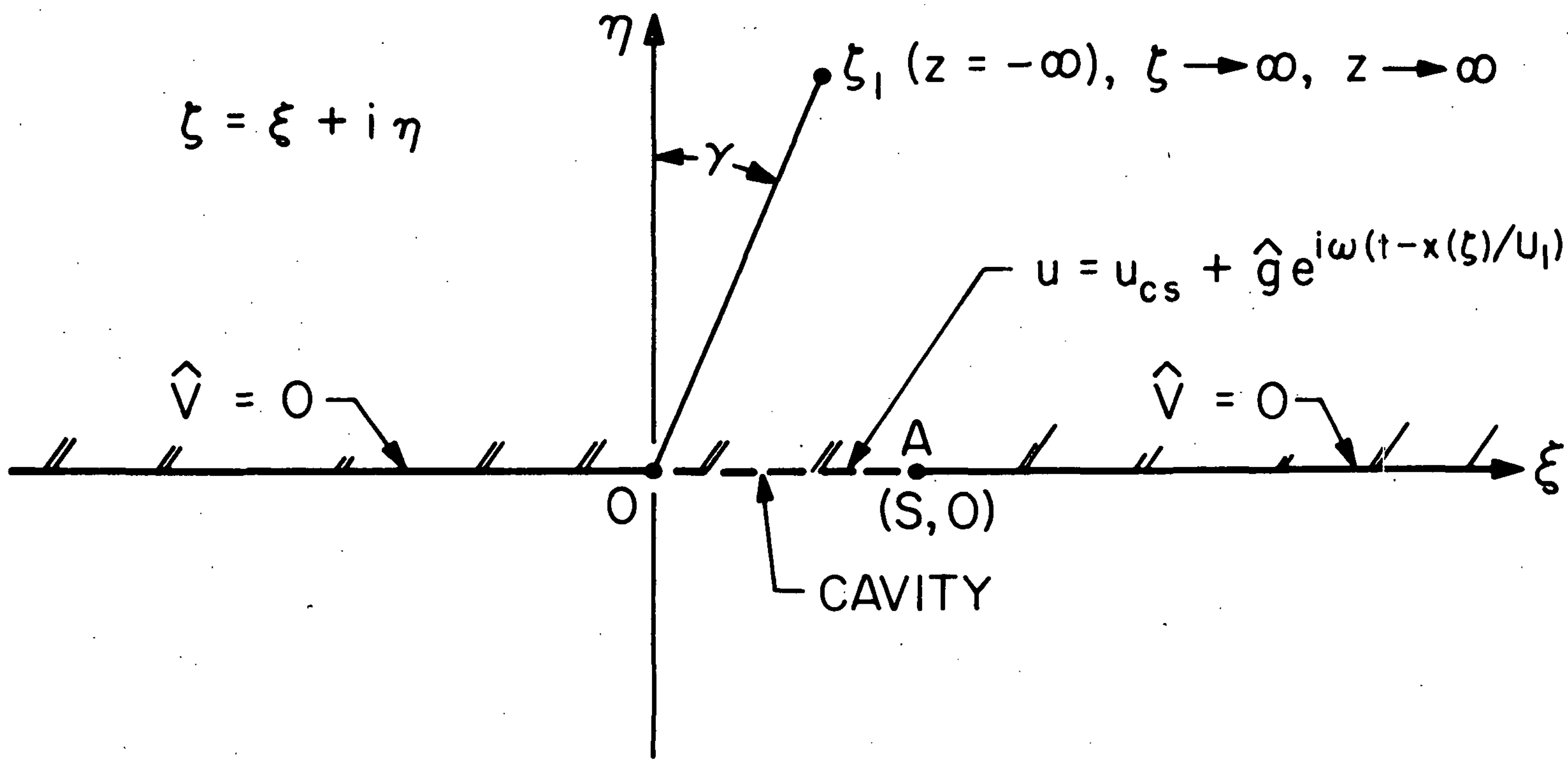

Figure 2. Transform Plane for Cavitating Inducer Cascade Showing Linearized Boundary Conditions.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (*Corporate author*) California Institute of Technology Pasadena, California 91109	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Dynamics of Cavitating Cascades

4. DESCRIPTIVE NOTES (*Type of report and inclusive dates*)

Research Report (final)

5. AUTHOR(S) (*First name, middle initial, last name*)

A. J. Acosta, C. Brennen and J. H. Kim

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 15, 1972	16	7

8a. CONTRACT OR GRANT NO. NAS 8-28046 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) E-184.1 9b. OTHER REPORT NO(S) (*Any other numbers that may be assigned this report*)

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY George C. Marshall Space Flight Ctr. NASA Marshall Space Flight Ctr. Alabama 35812

13. ABSTRACT

This final report contains brief accounts of the theoretical research conducted at the California Institute of Technology on the unsteady cavitation characteristics of liquid rocket engine turbopumps. The objective is to produce estimates of the cavitation compliance and other unsteady characteristics which could then be used in analysis of the POGO instability. Blade cavitation is the particular phenomenon which is investigated here and linearized free streamline methods have been employed in both quasistatic and complete dynamic cascade analyses of the unsteady flow. The simpler quasistatic analysis was applied to particular turbopumps but yielded values of compliances significantly smaller than those indirectly obtained from experiments. Reasons for this discrepancy are discussed. The complete dynamic analysis presents a new problem in fundamental hydrodynamics and, though the basic solution is presented, numerical results have not as yet been obtained.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Liquid Rocket Engines POGO Instability Cavitating Turbopump Blade Cavitation Compliance						