A Quasisteady Theory for Incompressible Flow Past Airfoils with Oscillating Jet Flaps

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Quasisteady concepts are used for an approximate analysis of incompressible flow past airfoils with harmonically oscillating jet flaps. The instantaneous flowfield is considered as a sequence in the streamwise direction of steady flows with a properly enforced tangency condition between the jet and the external flow. The jet kinematics are found from experimentally determined jet decay characteristics, and the time-frozen jet is modeled by using Spence's steady jet flap analysis. Computed lift response shows substantial agreement with available measurements.

I. Introduction

A JET flap results if air is ejected at an angle to the freestream from a spanwise slot at or near the trailing edge of an airfoil (Fig. 1). It produces lift both by the component of thrust in the lift direction and by the modification of circulation around the airfoil. The second effect is associated with differential generation of vorticity between the upper and lower shear layers of the curved jet sheet. The steady jet flap has received considerable attention because of interest in V/STOL aircraft. It was first analyzed on the basis of two-dimensional inviscid flow, thin airfoil, and thin jet theory by Spence.[1] Recently Halsey[2] has refined this approach by the inclusion of jet entrainment effects and by satisfaction of the flow tangency condition along the jet centerline.

Interest in unsteady jet flaps appears to have begun when W. R. Sears, according to Spence,[3] suggested the use of jet flaps for fast-acting lift control. Potential applications to helicopter rotors and aircraft mode stabilization systems have led to theoretical and experimental studies of two-dimensional incompressible flow past an oscillating airfoil-jet flap configuration.[4-7] Attempts to extend Spence's steady thin jet flap theory to the case of time-varying jet exit angle are due to Erickson[8] and Spence,[3,9] but solution of the resulting equations presents enormous difficulties. Spence proposed a weak jet approximation and succeeded in deriving an approximate solution for high frequencies. More recently, Potter[10] approached the oscillating jet flap problem as an initial value problem in time and used point vortex distributions in conjunction with finite-difference techniques, but erratic vortex motions tended to limit the procedure to low jet strengths. The dynamic condition for pressure difference across the jet was taken from Spence.[3]

Simmons[4] has shown a substantial agreement among his measurements of the frequency response of lift, those from other experiments,[7,11] and the limited predictions by Potter. However, the theory of Spence[3] shows directly opposite trends. In particular, it results in lift which leads jet deflection in phase, whereas the other studies indicate phase lags. Also the downstream boundary conditions do not approach those for the steady jet flap as frequency is reduced toward zero. These conflicts motivated Simmons et al.[12] to make detailed measurements of the instantaneous velocity field associated with an oscillating jet flap. Their findings have led to a review of thin jet flap theory in Sec. II and the quasisteady theory in Sec. III.

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II. Thin Jet Models

Steady Jet Flap

Spence[1] bases his successful model of the steady two-dimensional jet flap on a jet element which is separated along its boundaries from the external flow region by vortex sheets. The pressure difference ΔP across this element is related by Eq. (1) to the jet momentum flux J per unit span and the mean radius of curvature r of the element.

$$\Delta P = J/r \tag{1}$$

Spence obtains the thin jet model by considering the limit as the jet velocity tends to infinity while J is assumed to remain finite. It follows that the jet thickness and mass flow tend to zero, kinetic energy flux tends to infinity, and J becomes constant along the jet. The jet can then be represented by a single vortex distribution γ_J given by Eq. (2):

$$\gamma_J(x) = \tfrac{1}{2} b U_0 C_J / r(x) \tag{2}$$

where $C_J = J/(\tfrac{1}{2}\rho_0 U_0^2 b)$ is the jet momentum coefficient per unit span, U_0 and ρ_0 are the velocity and density of the freestream, and b is the chord length. In this model the jet momentum flux is regarded as a more important parameter than the jet velocity.

With prescribed small jet slope η at $x=b$ and zero jet slope at infinity downstream as boundary conditions and with the substitution of Eq. (5), Spence obtains Eqs. (3) and (4) for the distribution of jet slope $y_J'(x)$ and curvature $y_J''(x) = -1/r(x)$ in terms of a variable $g(x)$. This variable is related to $y_J(x)$ and $\gamma_J(x)$ by Eqs. (6) and (7).

$$\frac{g(\varphi)}{\eta C_J} = -\frac{\cos^3 \tfrac{1}{2}\varphi}{2\sin \tfrac{1}{2}\varphi}\left(\sin \tfrac{1}{2}\varphi + \frac{A_0 \sin^2 \tfrac{1}{2}\varphi}{\cos \tfrac{1}{2}\varphi} + \sin \tfrac{1}{2}\varphi \sum_{n=1}^{\infty} A_n \sin n\varphi\right) \tag{3}$$

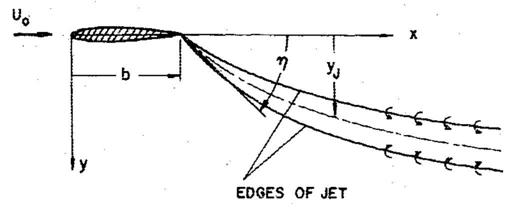

Fig. 1 Schematic of two-dimensional jet-flapped airfoil.

$$\frac{b}{\eta}\cdot\frac{dg(\varphi)}{dx} = 2\cos^3 \tfrac{1}{2}\varphi\left[-\frac{1}{\pi}\ln(\tan^2 \tfrac{1}{2}\varphi)+\sum_{n=0}^{\infty}A_n\cos n\varphi\right] \tag{4}$$

$$x/b = 1/\cos^2 \tfrac{1}{2}\varphi \tag{5}$$

$$g(x) = -\tfrac{1}{2}C_J y_J'(x) \tag{6}$$

$$\gamma_J(x) = bU_0 g'(x) = -\tfrac{1}{2}bU_0 C_J y_J''(x) \tag{7}$$

[Note that the equivalent of Eq. (4) in Spence's paper contains two typographical errors.] The A_n are Fourier coefficients and depend on C_J. From consideration of the total circulation, with γ_J treated as bound vorticity, it follows that the lift coefficient C_L is given by

$$C_L = 2\int_b^{\infty}\left(\frac{\xi}{\xi-1}\right)^{\frac{1}{2}} g'(\xi)\,d\xi \tag{8}$$

Unsteady Jet Flap

In steady jet flap theory the jet vorticity is treated as bound vorticity, and vorticity propagation aspects need not be considered. However, a complete unsteady jet flap analysis requires a detailed description of the mechanism of vorticity generation and propagation. Vorticity is transported in the shear layers with a velocity which, from physical considerations, depends on the ratio U_J/U_0 of a characteristic jet velocity to the freestream velocity. The omission of this parameter from the unsteady thin jet model of Erickson[8] and Spence[3,9] leads to difficulties.

Erickson and Spence claim that the pressure difference across an element of an unsteady jet is again given by Eq. (1) except that r is interpreted as the local radius of curvature of the instantaneous jet centerline. They obtain this dynamic jet condition by introducing the unsteady velocity potential into the Bernoulli equations for the jet element used in steady jet flap theory. The element is again collapsed to a single vortex sheet by allowing U_J to tend to infinity, while J is assumed to remain finite. In contrast to steady jet flap theory, Erickson and Spence are forced to apply a downstream boundary condition to obtain the dynamic condition for a jet element. To meet the requirement that the external flow should be undisturbed at infinity downstream, they introduce the boundary conditions

$$y_J = y_J' = y_J'' = 0 \quad \text{at } x=\infty \tag{9}$$

This leads to the physically unlikely situation that an oscillating jet, no matter how slow the oscillation might be, must return to a condition of zero jet deflection at downstream infinity, but must approach an infinite deflection for the limiting case of vanishing frequency of oscillation (i.e., Spence's steady jet shape). It can be shown that Eq. (9), together with the assumption of infinite U_J, forces Erickson's restriction that instantaneous streamlines of the flow within a jet element must be substantially parallel to the instantaneous jet boundaries.

The difficulties arising in the unsteady model of Erickson and Spence and the restriction on streamlines can be removed if the jet velocity is assumed to decay monotonically from a value much greater than U_0 at the trailing edge to U_0 at infinity downstream. A thin jet model can no longer be strictly formulated, but the rate of decay of the jet can be made so small that the thin jet assumption is reasonable over the limited range of x which, from the viewpoint of practical computation, is adequate for prediction of lift. Because development of the dynamic jet condition for an element of an unsteady decaying jet is likely to be difficult, the authors have studied the potential of a quasisteady model to resolve the discrepancies between available theoretical and experimental lift coefficients.

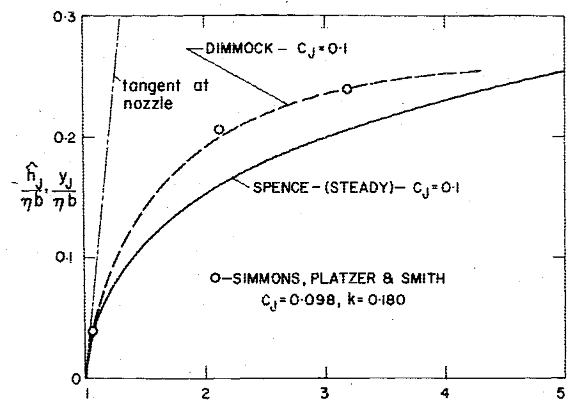

Fig. 2 Measured amplitude $\hat{h}_J$ of transverse oscillation of jet flap centerline (Simmons et al.[12]) and steady jet flap centerlines.

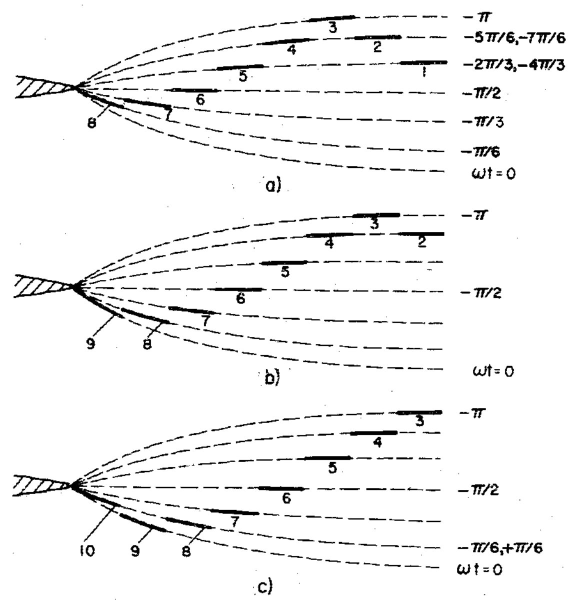

Fig. 3 Schematic of position of vorticity elements (solid lines) along steady jet paths (dashed lines) at three successive instants. a) $kU_0t/b = -\pi/6$, b) $kU_0t/b = 0$, c) $kU_0t/b = +\pi/6$. For a given frequency, times on path are those at which elements left nozzle.

III. Quasi-Steady Model

Physical Considerations

Simmons et al.[12] recently used hot-wire anemometry to measure the instantaneous velocity profiles for two-dimensional flow past an airfoil with oscillating jet flap. By studying the movement of the jet centerline, they found that at low frequencies the flow path lines within the jet are similar to those for the steady jet flap. The path lines showed no downstream tendency toward the chord line. This is shown in Fig. 2, where the amplitude $\hat{h}_J(x)$ of transverse oscillation of the jet centerline is compared with steady jet flap centerlines $y_J(x)$ measured by Dimmock[13] and predicted by Spence.[1]

These findings suggest the following quasisteady model. The jet is idealized by a single vortex sheet divided in the x direction into infinitesimal vorticity elements. Each element is assumed to travel along a path which is insignificantly perturbed from the steady jet centerline corresponding to the jet exit angle at the time of ejection of the element (Fig. 3). The transport velocity of each vorticity element is obtained from knowledge of the decay of velocity profiles. The instantaneous flow is then regarded as a sequence in the x direction of steady jet flows. Compatibility between the steady flows associated with adjacent vorticity elements is obtained through satisfaction of the flow tangency between the vortex sheet and the adjacent external flow. In this way each vorticity element is assigned an instantaneous distribution of vorticity which is related through Eq. (7) to the instantaneous local radius of curvature of path lines of external particles adjacent to the jet. The quasisteady model thus comprises the dynamic jet equation from steady jet flap theory and assumed quasisteady kinematics.

Mathematical Formulation

The mathematical model is restricted to the two-dimensional flow past a thin airfoil at zero incidence. The jet flap exit angle η varies harmonically with frequency ω through small angles about the chord line so that

$$\eta(t) = Re[\hat{\eta}e^{j\omega t}] \tag{10}$$

where Re denotes the real part of the complex quantity and $j=\sqrt{-1}$. The instantaneous jet shape is expressed as

$$h_J(x,t)/b = Re[\bar{y}_J(x)\hat{\eta}e^{j\omega(t-\tau)}] \tag{11}$$

Here $\bar{y}_J(x)$ is the steady jet shape for unit η and b obtained by Spence.[1] The transport time τ of a vorticity element from the trailing edge to x is given in terms of a local characteristic jet velocity by Eq. (12).

$$\tau(x) = \int_b^x \frac{\mathrm{d}x}{U_J(x)} \tag{12}$$

The instantaneous lift is given by Eq. (8) but g' is now a separable function of x and t and is obtained through Eq. (7) from the curvature of particle paths adjacent to the jet.

To determine the curvature of these particle paths use is made of the fact that for small $\hat{\eta}$ and ω both the direction and the x component of velocity of the external flow are only slightly perturbed from freestream conditions. The y component $v_p(x,t)$ of velocity of an external flow particle adjacent to the jet and displaced $h_p(x,t)$ from the chord line is obtained from the flow tangency condition:

$$v_p(x,t) = \frac{Dh_p(x,t)}{Dt} = \left(\frac{\partial}{\partial t} + U_0\frac{\partial}{\partial x}\right)\cdot h_J(x,t) \tag{13}$$

Similarly, the y component of acceleration of this particle is

$$a_p(x,t) = \frac{Dv_p(x,t)}{Dt} = \left(\frac{\partial}{\partial t} + U_0\frac{\partial}{\partial x}\right)\cdot v_p(x,t) \tag{14}$$

In this linearized model, the radius of curvature $r_p(x,t)$ of the external flow particle paths is

$$r_p(x,t) = U_0^2/a_p(x,t) \tag{15}$$

Inserting Eqs. (13-15) into Eqs. (11) and (12), and neglecting terms of $O(\omega^2)$ yields Eq. (16) for the curvature $1/r_p$ of particle paths:

$$\frac{1}{\hat{\eta}br_p(x,t)} = \frac{\partial^2\bar{y}_J(x)}{\partial x^2}\cos\omega(t-\tau) - \omega\left[\frac{\bar{y}_J}{U_J^2(x)}\cdot\frac{\partial U_J(x)}{\partial x} + 2\frac{\partial\bar{y}_J(x)}{\partial x}\cdot\left(1-\frac{U_0}{U_J(x)}\right)\frac{1}{U_0}\right]\sin\omega(t-\tau) \tag{16}$$

Computation of the terms in Eq. (16) using realistic parameters shows that the term containing $\partial U_J/\partial x$ is insignificant, even though $\bar{y}_J(x)$ tends to infinity logarithmically. The term is omitted at this stage from the model.

It is convenient to introduce dimensionless lengths $\bar{x}=x/b$, $\bar{r}_p=r_p/b$, the reduced frequency $k=\omega b/U_0$, dimensionless time $\bar{t}=tU_0/b$, and the velocity ratio $R(\bar{x})=U_J(\bar{x})/U_0$, so that Eq. (16) can be written as

$$\frac{1}{\hat{\eta}\bar{r}_p} = \frac{\partial^2\bar{y}_J}{\partial\bar{x}^2}\cos k(\bar{t}-\bar{\tau}) - 2k\frac{\partial\bar{y}_J}{\partial\bar{x}}(1-1/R(\bar{x}))\sin k(\bar{t}-\bar{\tau}) \tag{17}$$

where

$$\bar{\tau} = \int_1^{\bar{x}}\frac{\mathrm{d}\bar{x}}{R(\bar{x})} \tag{18}$$

The lift coefficient $C_L(\bar{t})$ can now be evaluated by inserting $\bar{r}_p$ into Eq. (7) and the dimensionless form of Eq. (8). Thus,

$$C_L(\bar{t}) = -C_J\int_1^\infty\left(\frac{\xi}{\xi-1}\right)^{1/2}\cdot\frac{1}{\bar{r}_p}\mathrm{d}\xi \tag{19}$$

The component of lift coefficient C_{LR} in phase with the jet exit angle $\eta=\hat{\eta}\cos k\bar{t}$ is obtained by setting $\bar{t}=0$ in Eq. (17). Similarly, the quadrature component of lift coefficient C_{LI} is obtained by setting $k\bar{t}=3\pi/2$. Thus,

$$\frac{C_{LR}}{\hat{\eta}} = -C_J\int_1^\infty\left(\frac{\bar{x}}{\bar{x}-1}\right)^{1/2}\left(\frac{\partial^2\bar{y}_J}{\partial\bar{x}^2}\cos(-k\bar{\tau}) - 2k\frac{\partial\bar{y}_J}{\partial\bar{x}}\left[1-\frac{1}{R(\bar{x})}\right]\sin(-k\bar{\tau})\right)\mathrm{d}\bar{x} \tag{20}$$

$$\frac{C_{LI}}{\hat{\eta}} = -C_J\int_1^\infty\left(\frac{\bar{x}}{\bar{x}-1}\right)^{1/2}\left(\frac{\partial^2\bar{y}_J}{\partial\bar{x}^2}\cos k(3\pi/2-\bar{\tau}) - 2k\frac{\partial\bar{y}_J}{\partial\bar{x}}\left[1-\frac{1}{R(\bar{x})}\right]\sin k(3\pi/2-\bar{\tau})\right)\mathrm{d}\bar{x} \tag{21}$$

IV. Computation of Lift Coefficient

Jet Decay Data

For the case of a turbulent jet flap with $\eta=0$, Bradbury and Riley[14] have shown that the decay of jets with different ratios R_J of nozzle velocity to freestream velocity can be collapsed into a universal curve. Their measurements, presented in terms of the jet momentum thickness $\theta=\frac{1}{2}b\,C_J$ and the excess U_I of the jet centerline velocity over the freestream velocity, lie generally between the two lines given by

$$\left(\frac{U_0}{U_I}\right)^2 = \beta\left(\frac{x-1-x_0}{\theta}\right) \tag{22}$$

where $\beta=0.16$ close to the nozzle, and $\beta=0.41$ further downstream. Here x_0 is the shift of the effective jet origin from the nozzle exit and is related to the potential core. Dimmock[13] and Simmons et al.[12] have measured more rapid velocity decay in steady and oscillating jet flaps, respectively, with nonzero η, but their results are not extensive. In this investigation $\beta = 0.3$ is taken as representative for all x, but a sensitivity analysis is made.

The vorticity element transport velocity $U_j(x)$ is now taken as $U_j + U_0$ and is introduced into Eq. (22). The fact that $U_J/U_0 = R_J$ at $\bar{x} = 1$ is used to eliminate x_0, and the resulting Eq. (23) furnishes the jet decay in the computations:

$$R(\bar{x}) = 1 + \left(\frac{C_J}{2\beta\bar{x} + C_J/(R_J - 1)^2}\right)^{1/2} \tag{23}$$

Numerical Integration

The dependence of lift coefficient on frequency has been computed over a limited range of parameters by numerical integration of Eqs. (20) and (21). The integrands in Eqs. (20) and (21) exhibit a singularity at $\bar{x} = 1$ and rapidly approach zero as $\bar{x}$ is increased. Integration from $\bar{x} = 1 + 3.125 \times 10^{-11}$ to the downstream limit (viz $\bar{x} = 20$ for $C_J = 0.383$ and $\bar{x} = 10$ for $C_J = 0.1$) yields lift coefficents at zero frequency within about 5% of those determined by Spence[1] for the steady jet flap. The singularity causes no numerical difficulty over the range of $\bar{x}$. A similar accuracy can be assigned to in-phase and quadrature components of quasisteady lift coefficient. In this study the first 28 terms of the Fourier series A_n were computed [Eqs. (3) and (4)].

Frequency Response of Lift

The frequency response of the lift coefficient

$$C_L(\bar{t}) = Re[\,|C_L(k)|\,e^{j[k\bar{t} + \Psi(k)]}] \tag{24}$$

to the jet oscillation $\eta = Re\,[\hat{\eta}e^{jk\bar{t}}]$ was computed for values of C_J and R_J, which enables a comparison with measurements by Simmons.[4] The phase angle $\Psi(k)$ is plotted in Fig. 4, its negative value indicating that lift lags jet oscillation. The quasisteady theory should be limited to frequencies k below about 0.1, but results at higher frequencies are included to show trends. The phase angle Ψ is rather insensitive to variation of the jet velocity over a realistic range. However, better agreement with measured phase angles is obtained if

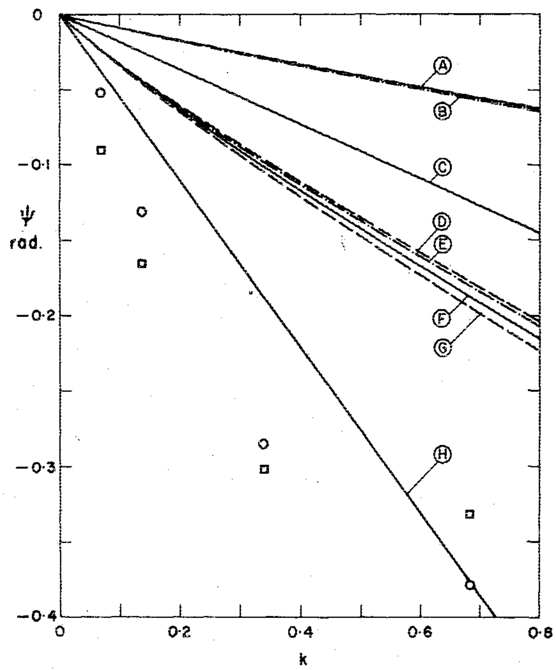

Fig. 4 Frequency response of phase angles computed from quasisteady theory. A, ($C_J = 0.1$, $R_J = 5$, $\beta = 0.3$); B, (0.1, 10, 0.3); C, (0.1, ∞, 0); D, (0.383, 10, 0.5); E, (0.383, 5, 0.3); F, (0.383, 10, 0.3); G, (0.383, 10, 0.2); H, (0.383, ∞, 0). Measurements by Simmons[4] — ○, ($C_J = 0.099$, $R_J = 5$); □, (0.383, 10).

$R(\bar{x}) \gg 1$ over the range of integration. This assumption implies that jet decay is insignificant over the range of integration. The term $[\bar{x}/(\bar{x} - 1)]^{1/2}$ insures that the integrands in Eqs. (20) and (21) still converge, although 40 chord lengths are now needed to get 5% accuracy.

Although the experimental trend of increasing phase lag with C_J is predicted, the theoretical phase lags are significantly less than those measured. Apart from the limitations of the model, three other factors should be mentioned in this regard. First, there are very few measurements at frequencies below $k = 0.1$. Second, the angles involved are small, no more than 5 deg at $k = 0.1$, and experimental uncertainty could account for much of the discrepancy. Third, the theory is sensitive to conditions in the vicinity of the trailing edge. It does not include the local viscous effects which might be important in tests of an airfoil with truncation of the trailing edge to house the nozzle. A preliminary study, in which the singularity in vorticity distribution at $\bar{x} = 1$ [Eq. (4)], was weakened yielded about 50% increase in the magnitude of phase lags. This was achieved without affecting steady lift and with better agreement between measured and predicted jet shapes near the trailing edge.

The computed values of $|C_L(k)|$ have not been plotted because they were less than 2% below the steady value ($k = 0$) at frequencies up to $k = 0.2$. The trend of decreasing $|C_L|$ with increasing k is in keeping with Simmons[4] measurements.

V. Conclusions

Quasisteady flow concepts have been used for an approximate analysis of incompressible flow past airfoils with harmonically oscillating jet flaps. In this model the instantaneous flowfield is considered as a sequence in the streamwise direction of steady flows with a properly enforced tangency condition between the jet flow and the external flow. The jet kinematics are then found from experimentally determined jet decay characteristics. The jet dynamics are obtained from the relationship between jet vorticity and the local curvature of particle path lines adjacent to the jet.

Application of Spence's steady jet flap analysis to the time-frozen jet yields a lift response in substantial agreement with the available experiments. Although the major flow features displayed by slowly oscillating jet flaps are described, a more exact analysis is required in order to assess more clearly the limitations of this approach. In particular, it should be noted that the phase lag in lift response largely originates through the flow tangency condition, with no attempt being made to model the precise vorticity propagation mechanism. Full evaluation of this use of an equivalent bound vorticity distribution—even within a small frequency theory—and development of a theory valid for arbitrary frequencies remain tasks for future research.

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