Computation of tow loads on a liferaft in a surface wave

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COMPUTATION OF TOW LOADS ON A LIFERAFT IN A SURFACE WAVE

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Abstract: A numerical model for the coupled dynamics of a small liferaft and fast rescue craft in a surface wave is presented. The equations are formulated in 2D using the methods of Kane and Levinson (1985) and solved numerically using a MATLAB® Runge-Kutta routine. It is assumed that the motion normal to the wave surface is small and can be neglected, i.e. the bodies move along the propagating wave profile. The bodies are small so that wave diffraction and reflection are negligible. A Stokes' second order wave is used and the wave forces are applied using Morison's equation for a body in accelerated flow. Wind loads are similarly modeled using drag coefficients. Comparison with model tests performed at the Institute for Ocean Technology shows good agreement. The model provides guidelines for predicting the tow loads and motions of small craft in severe sea states.

Keywords: Liferaft, Fast Rescue Craft, Towing, Coupled Dynamics

1. INTRODUCTION

Liferafts are an important means of emergency evacuation from many sea going vessels and petroleum installations. However their operational performance in varying sea states is largely unknown. Current IMO regulations require liferafts to be towed in calm water conditions to achieve certification. As many marine disasters happen in less than ideal weather conditions, additional information on liferaft performance capability in medium to high sea states would help improve rational decision-making processes governing a host of associated search and rescue operations. The problem of a single small body in waves was addressed by Marchenko[1] using a vectorial approach and by Grotmaack and Meylan[2] using Hamilton's Principle. These works are based on a slope sliding model and lead to the same equation of motion. Here we consider the coupled motions of two bodies on a surface wave, representing the fast rescue craft (FRC) and the liferaft. The wave is described by standard formulae for a Stokes second order wave. It is assumed that the dimensions of both bodies are small relative to the wavelength (less than one-fifth of the wavelength) so that wave reflection and diffraction are negligible.We also assume that the motion of the bodies normal to the wave surface is small and can be neglected. The governing equations are derived using Kane's equations of motion [3] and solved numerically. The results are compared with physical model test results.

2. KINEMATICS

The problem is illustrated in Fig 1. Point O is the origin of a fixed inertial coordinate system with x axis at the mean sea level and and z axis pointing vertically upwards. A small liferaft is being towed by a Fast Rescue Craft (FRC), both constrained to move on the surface of a wave which is propagating in the positive x direction

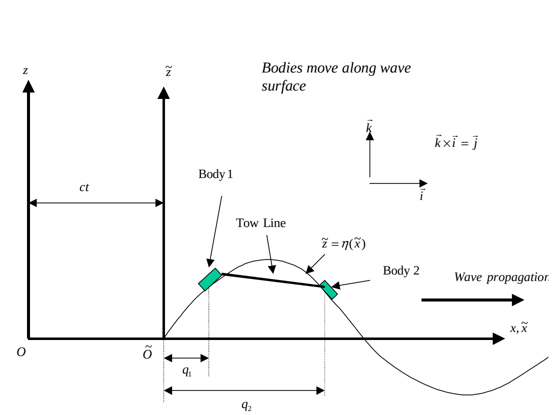

Fig. 1. Configuration

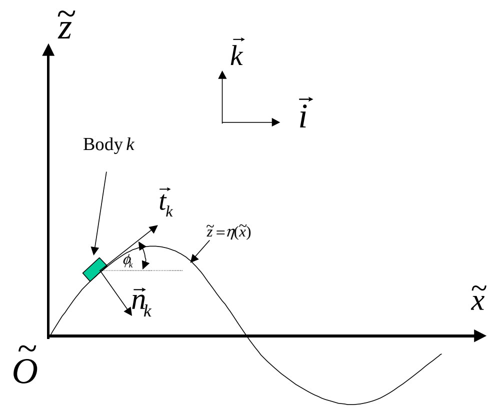

Fig. 2. Orientation of body k

with speed c. In a following sea, the liferaft and FRC are identified as body 1 and 2 respectively, and in a head sea this designation is reversed. The dimensions of both bodies are small relative to the wavelength and we assume that their drafts do not change. Point $\widetilde{O}$ is the origin of a coordinate system (axes $\widetilde{x}, \widetilde{z}$) moving with the wave speed c in the positive x direction. The unit vectors of both systems are $\overrightarrow{i}, \overrightarrow{k}$ in x, z directions respectively and $\widetilde{x} = x - ct$ where t is time. The equation of the wave profile in the moving coordinate system is

$$\widetilde{z} = \eta\left(\widetilde{x}\right) \qquad (1)$$

where η is a specified function. At time t, the position of body k relative to the moving $\widetilde{O}\widetilde{x}\widetilde{z}$ frame is (q_k, η_k) where $\eta_k = \eta\left(q_k\right),\ k = 1,2.$ The generalised coordinates are q_1, q_2 and we define the generalised speeds as $u_r = \dot{q}_r\ \ (r = 1,2)$ where the dot indicates differentiation with respect to time. The unit tangential vector to the wave surface at body k is denoted by $\overrightarrow{t_k}$ illustrated in Fig.2 and is given by

$$\overrightarrow{t_k} = \left(\overrightarrow{i} + \eta_k' \overrightarrow{k}\right) Z_k^{-\frac{1}{2}} \qquad (2)$$

where $Z_k = 1 + \left(\eta_k'\right)^2,\ \eta_k' = \frac{\partial}{\partial q_k}\left(\eta_k\right),\quad k = 1,2.$

The position vector $\overrightarrow{r_k}$, velocity $\overrightarrow{v_k}$ and acceleration $\overrightarrow{a_k}$ of body k are given by

$$\overrightarrow{r_k} = \left(q_k + ct\right)\overrightarrow{i} + \eta_k \overrightarrow{k} \qquad (3)$$

$$\overrightarrow{v_k} = \left(u_k + c\right)\overrightarrow{i} + \eta_k' u_k \overrightarrow{k} \qquad (4)$$

$$\overrightarrow{a_k} = \dot{u}_k \overrightarrow{i} + \left(\dot{u}_k \eta_k' + u_k^2 \eta_k''\right)\overrightarrow{k} \qquad (5)$$

where $\eta_k'' = \frac{\partial^2}{\partial q_k^2}\left(\eta_k\right),\quad k = 1,2.$ If ϕ_k is the angle made by the tangent vector $\overrightarrow{t_k}$ with the positive x direction, the angular velocity and angular acceleration of body k are respectively $\overrightarrow{\omega}_k = -\dot{\phi}_k \overrightarrow{j}$ and $\overrightarrow{\alpha_k} = \dot{\overrightarrow{\omega_k}}$, and evaluated as

$$\overrightarrow{\omega_k} = -\left(\frac{\eta_k'' u_k}{Z_k}\right)\overrightarrow{j} \qquad (6)$$

$$\overrightarrow{\alpha_k} = -\left\{\frac{\eta_k'' \dot{u}_k}{Z_k} + \frac{u_k^2}{Z_k^2}\left(\eta_k''' Z_k - 2\eta_k' \left(\eta_k''\right)^2\right)\right\}\overrightarrow{j} \qquad (7)$$

where $\eta_k''' = \frac{\partial^3}{\partial q_k^3}\left(\eta_k\right),\quad k = 1,2.$ The partial velocities $\overrightarrow{v}_{kr}$ and partial angular velocities $\overrightarrow{\omega}_{kr}$ of body k are written by inspection as (Kane and Levinson, 1985)

$$\begin{aligned} \overrightarrow{v}_{kr} &= \delta_{kr}\left(\overrightarrow{i} + \eta_k' \overrightarrow{k}\right) \\ \overrightarrow{\omega}_{kr} &= -\delta_{kr}\left(\frac{\eta_k''}{Z_k}\right)\overrightarrow{j} \end{aligned} \qquad (k = 1,2\ ;\ r = 1,2) \qquad (8)$$

where δ_{kr} is the Kronecker delta.

3. FORCES

3.1 Environmental Forces

Let the mass of body k be m_k and its moment of inertia about its central axis parallel to the $\overrightarrow{j}$ direction be I_k. The generalised inertia force (non-hydrodynamic) on body k is $G_{kr}^* = \overrightarrow{v}_{kr} \cdot \left(-m_k \overrightarrow{a}_k\right) + \overrightarrow{\omega}_{kr} \cdot \left(-I_k \overrightarrow{\alpha}_k\right)$ $, r = 1,2$. This may be written in the form

$$G_{kr}^* = \left(A_k \dot{u}_k + B_k\right)\delta_{kr} \quad , \quad (k, r = 1,2) \qquad (9)$$

where A_k and B_k depend on the inertia properties of the bodies and the geometry of he wave profile. We write the external force $\overrightarrow{F_k}^E$ on body k as the sum of forces due to gravity ($\overrightarrow{F}_k^G$), waves ($\overrightarrow{F_k}^{\text{wave}}$), wind ($\overrightarrow{F}_k^{\text{wind}}$) and propulsion ($\overrightarrow{F_k}^P$). The associated generalised force is $G_{kr} = \overrightarrow{v}_{kr} \cdot \overrightarrow{F_k}^E$ which can be written as

$$G_{kr} = Z_k^{\frac{1}{2}} \overrightarrow{t}_k \cdot \overrightarrow{F_k}^E \delta_{kr}\ ,\ (k, r = 1,2) \qquad (10)$$

The gravitational force is $\overrightarrow{F}_k^G = -m_k g \overrightarrow{k}$ where m_k is the mass of body k and g is the acceleration due to gravity. The wave force $\overrightarrow{F_k}^{\text{wave}}$ on body k is written as (Sumer and Fredsoe[4])

$$\overrightarrow{F_k}^{\text{wave}} = \overrightarrow{F_k}^{FK} + \overrightarrow{F_k}^{A} + \overrightarrow{F_k}^{D} \qquad (11)$$

where $\overrightarrow{F_k}^{FK}$ is the Froude-Krylov force, $\overrightarrow{F_k}^{A}$ is the inertial force due to added-mass and $\overrightarrow{F_k}^{D}$ is the wave drag force. Let $\overrightarrow{v}_k^F, \overrightarrow{a}_k^F$ be the water particle velocity and acceleration respectively at body k. The x and z components of $\overrightarrow{v}_k^F, \overrightarrow{a}_k^F$ are denoted by $\left(u_k^F, w_k^F\right)$ and $\left(a_{x,k}^F, a_{z,k}^F\right)$ respectively. The velocity and acceleration of body k relative to the water are, respectively $\overrightarrow{v}_k^R = \overrightarrow{v}_k - \overrightarrow{v}_k^F$ and $\overrightarrow{a}_k^R = \overrightarrow{a}_k - \overrightarrow{a}_k^F$. The Froude-Krylov force is $\overrightarrow{F_k}^{FK} = \rho V_k^F \overrightarrow{a}_k^F$, the added-mass force is $\overrightarrow{F_k}^{A} = -m_{a,k}\overrightarrow{a}_k^R$ and the drag force is $\overrightarrow{F_k}^{D} = -\frac{1}{2}\rho A_k^F C_{D,k}^F \left|\overrightarrow{v_k}^R\right| \overrightarrow{v}_k^R$, where ρ is the water density, V_k^F is the submerged volume of body k, A_k^F is the projected wetted area of body k normal to the tangent vector $\overrightarrow{t}_k$, $C_{D,k}^F$ is the associated drag coefficient, and $m_{a,k}$ is the added-mass of body k for surge motion.

The wind force is due to drag and is written as $\overrightarrow{F}^{\text{W}} = -\frac{1}{2}\rho_{\text{air}} A_k^{\text{W}} C_{D,k}^{\text{W}} \left|\overrightarrow{v}_k - \overrightarrow{v}_{\text{W}}\right| \left(\overrightarrow{v}_k - \overrightarrow{v}_{\text{W}}\right)$, where ρ_{air} is the air density, $\overrightarrow{v}_{\text{W}} = v_x^{\text{W}}\ \overrightarrow{i}$ is the wind velocity, A_k^{W} is the projected area of body k normal to $\overrightarrow{t}_k$ and $C_{D,k}^{\text{W}}$ is the associated wind drag coefficient. The propulsive force on body k is assumed to be parallel to the wave surface and written as $\overrightarrow{F_k}^{P} = F_k^P \overrightarrow{t}_k$. We can then write equation (10) in the form

$$G_{kr} = \left(C_k \dot{u}_k + D_k\right)\delta_{kr} \quad , \quad (k, r = 1, 2) \quad (12)$$

3.2 Interaction Forces (Tow Line)

The tow-line tension on each body is equivalent to a force-couple system at the centre of mass of each body. Since we are neglecting local rotations relative to the wave surface, the couples are resisted by opposing couples from the wave surface. We therefore consider only the effect of the tow-line tension at the centres of mass of the bodies. The line stiffness is denoted by k_T and the unstretched length is L_0. In order to allow for tension but not compression we write the tow-line tension in the form $k_T Y_2$ where $Y_2 = \frac{1}{2}\left\{(Y_1 - L_0) + |Y_1 - L_0|\right\}$ and Y_1 is the instantaneous length of the tow-line, computed from the positions of the two bodies. The magnitude of the damping force is the product of a damping coefficient c_T and the component of the relative velocity between the bodies along the tow line. If $\overrightarrow{e}$ is the unit vector along the tow-line from body 1 to body 2 and the velocity of body 2 relative to body 1 is denoted by $\overrightarrow{v}^{2\text{rel}1}$, the damping force on body 1 is $c_T Y_3$ where $Y_3 = \left(\overrightarrow{v}^{2\text{rel}1} \cdot \overrightarrow{e}\right)\text{sign}(Y_2)$. We will assume that when the bodies are moving towards each other the line damping is negligible. This means that we write the damping force in the tow line as $c_T Y_4$ where $Y_4 = \frac{1}{2}\left(Y_3 + |Y_3|\right)$. The force on body k due to the tow line is then

$$\overrightarrow{F_k}^{\text{Towline}} = \chi_k \overrightarrow{e} \qquad (13)$$

where $\chi_1 = k_T Y_2 + c_T Y_4$ and $\chi_2 = -\chi_1$. The generalised force on body k due to the tow line is $G_{kr}^{\text{Towline}} = \overrightarrow{v}_{kr} \cdot \overrightarrow{F_k}^{\text{Towline}}$ which is evaluated as

$$G_{kr}^{\text{Towline}} = E_k \delta_{kr} \qquad (14)$$

where

$$E_k = \left(e_x + \eta_k' e_z\right)\chi_k \qquad (k = 1, 2) \qquad (15)$$

and e_x, e_z are the x, z components of unit vector $\overrightarrow{e}$.

4. EQUATIONS OF MOTION

The equations of motion are [3]

$$\sum_{k=1}^{2}\left(G_{kr}^{*} + G_{kr} + G_{kr}^{\text{Towline}}\right) = 0 \quad (r = 1, 2) \quad (16)$$

Using equations (9), (12) and (14), we find from (16)

$$\dot{u}_r = -\left(\frac{B_r + D_r + E_r}{A_r + C_r}\right) \qquad (r = 1, 2) \quad (17)$$

Define the four-dimensional vector $\{y\}$ as $\{y\}^T = (q_1\ q_2\ u_1\ u_2)$. The dynamic system is then represented by the equation

$$\left\{\dot{y}\right\} = \begin{pmatrix} u_1 \\ u_2 \\ \dot{u}_1 \\ \dot{u}_2 \end{pmatrix} \qquad (18)$$

which is solved by the MATLAB® routine "ode45" with specified initial conditions.

5. EXPERIMENTAL VALIDATION

A physical model, 1:7 scale, of a typical 16-person liferaft was used in experiments that took place at the Clear Water Towing Tank (CWTT) at the Institute for Ocean Technology (IOT), part of the National Research Council of Canada (NRC), in St. John's, Newfoundland. The tank itself is 200m long, 12m wide, 7m deep and is fitted on one end with a dual-flap wave-maker and at the other end with a parabolic beach. The model liferaft was fitted with a custom built low power mini motion-measuring unit. The mini motion-measuring unit recorded accelerations and rates in the horizontal and vertical planes. The model liferaft was also

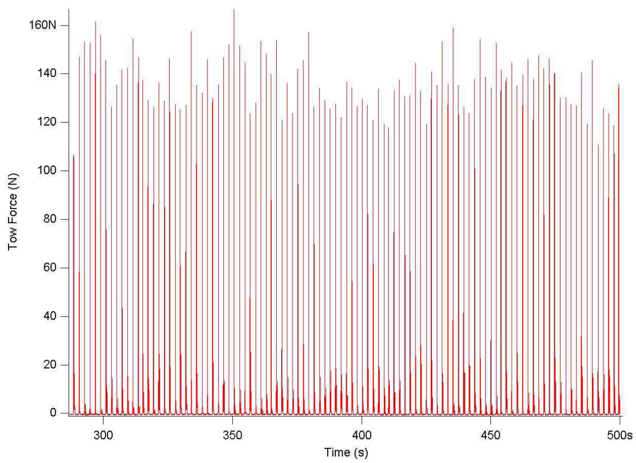

Fig. 3. Tow Line Tension : Physical Model Test

outfitted with reflector markers that allowed their real time motions to be measured and recorded using the optical tracking system (Qualysis). The model FRC contained a custom-built mini motion measuring unit similar to the one in the raft. The FRC unit was mounted approximately at the FRC's center of gravity. The tow forces were measured with a 100 N S-type load cell. The following parameters were used for the simulations of the model-scale experiments.

- *Fast Rescue Craft :* Mass=7.454 kg, Moment of inertia about pitch axis=0.889 $kg.m^2$, Added mass coefficient in surge =0.1, Drag coefficient = 0.007, Wetted surface area=0.27 m^2, Propulsive thrust = 7.498 N
- *16-person liferaft :* Mass=3.852 kg, Moment of inertia about pitch axis=0.0602 $kg.m^2$, Added mass coefficient in surge =0.2, Drag coefficient = 0.1, Wetted surface area=0.196 m^2
- *Tow Line :* Diameter = 0.95 mm, Length= 4.28 m, Modulus of Elasticity = 4.6 GPa, Damping constant=50 $N.\sec.m^{-1}$.

The measured tow line tension in a wave of height 0.456 m, period 2.229 sec is shown in Fig.(3).

This can be compared with Fig.(4) which shows the tow line tension predicted by the numerical model. Both figures show snap loads occurring at wave frequency with the numerical model slightly overestimating the peak loads. The measured mean forward speed of the FRC in the test was 0.271 m/s, and the value predicted by the numerical model is 0.223 m/s. We believe these differences are due to uncertainties in estimation of the parameters required by the numerical model.

6. RESULTS

We use the numerical model to predict the tow loads for the towing of a 16-person liferaft in a wave of height 1.3 m, period 7 sec. , wavelength

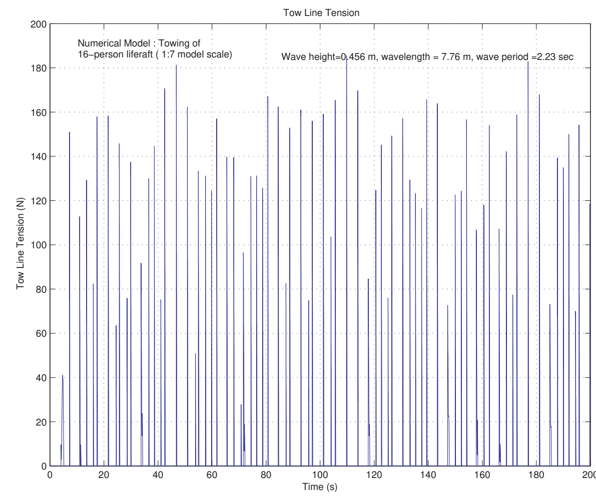

Fig. 4. Tow Line Tension : Numerical Model

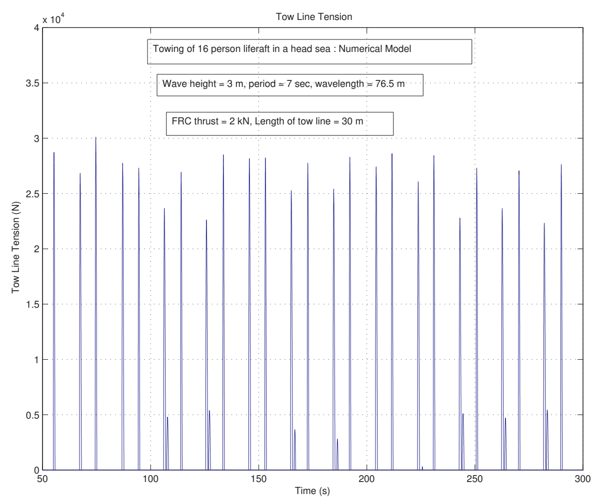

Fig. 5. Tow Line Tension : Short Tow Length

76.5 m. The following parameters were used for the simulation.

- *Fast Rescue Craft :* mass=2621 kg, moment of inertia about pitch axis=14941 $kg.m^2$, added mass coefficient in surge =0.1, drag coefficient = 0.007, wetted surface area=13.25 m^2, propulsive thrust = 2000 N
- *16-person liferaft :* Mass=1321 kg, moment of inertia about pitch axis=1012 $kg.m^2$, added mass coefficient in surge =0.2, drag coefficient = 0.1, wetted surface area=9.60 m^2
- *Tow Line :* diameter =20 mm, length=30 m and 76.5 m, modulus of elasticity =2 GPa, damping constant=1.29×10^3 $N.\sec.m^{-1}$.

The tow line tensions predicted by the numerical model are shown in Figure (5) for a tow line length of 30 m and in Figure (6) for a tow line length equal to the wavelength. For the head sea with FRC thrust of 2 kN, the peak snap loads are about 28 kN − 30 kN . If the tow line length is made equal to the wavelength, the simulation shows that both bodies are synchronised with

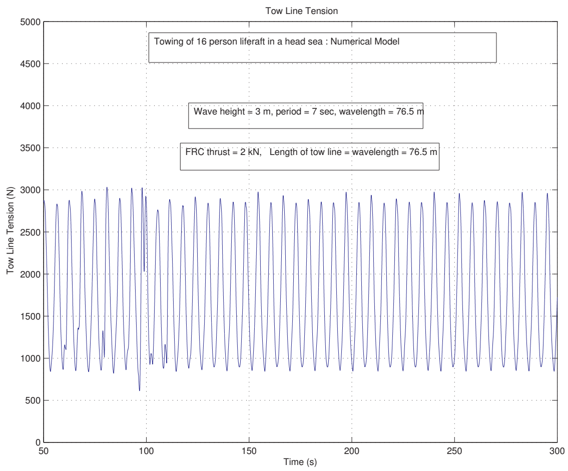

Fig. 6. Tow Tension : Tow Length Equal to Wavelength

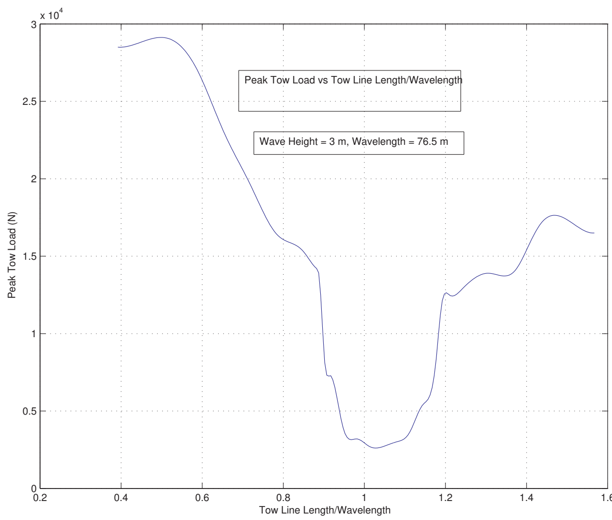

Fig. 7. Effect of Tow Line Length

respect to the wave, i.e. they are located at wave peaks or troughs at the same time. This causes a significant decrease in the tow loads, the peak load being 3 kN with no snapping as shown in Fig (6). This reduction in tow loads has also been observed in physical model tests and full scale trials. The effect of the tow line length on the peak tow loads is illustrated in Fig.(7), which shows that a significant reduction in peak tow loads is achieved when the tow line length differs from the wavelength by about 20%.

7. CONCLUSIONS

The coupled equations of motion for the towing of a small liferaft by a fast rescue craft have been formulated and solved numerically. There is good agreement between the physical and numerical model results in both the magnitude and frequency of the tow loads. The numerical model can be used by designers, manufactures and regulators in the preliminary stages of liferaft tow patch design as well as determination of the thrust required for liferaft towing. The model may also be used in the selection of tow line length and elasticity for the reduction of snap loading. We expect that such information will be useful in designing the liferafts and tow lines against structural failure and assist regulatory agencies in setting appropriate safety standards.

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