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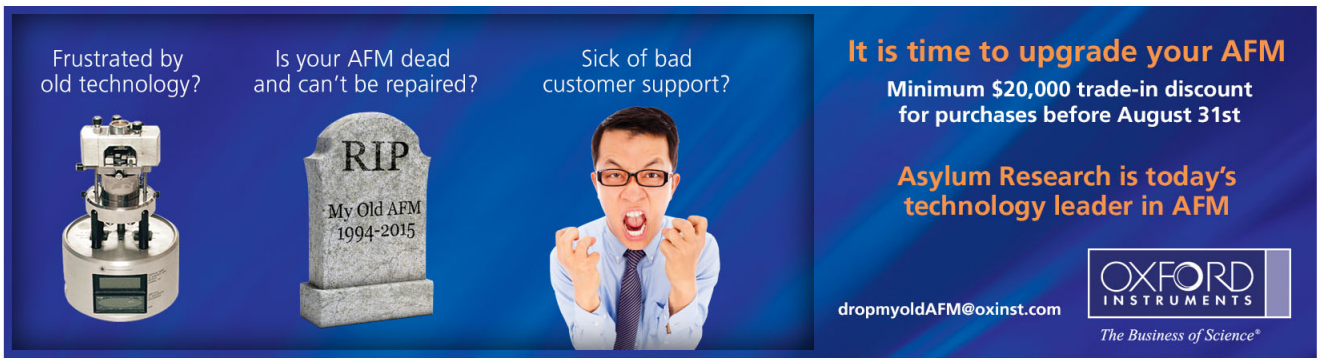
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Anomalous behaviour of leaky surface waves for stiffening layer near cutoff

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The propagation of surface acoustic waves has been investigated for a layered system (water-isotropic layer-isotropic substrate) where the layer is faster than the substrate. It has been found that when the velocity of the surface wave reaches the velocity of the shear wave of the substrate (cutoff) the behaviour of the attenuation has an anomalous character. Attenuation drops down towards zero below cutoff and increases abruptly beyond cutoff. Acoustic microscopy measurements on aluminum coated with oxalic oxide film were in coincidence with theory. © *1997 American Institute of Physics.* [S0021-8979(97)07915-2]

I. INTRODUCTION

Although many publications consider propagation of surface acoustic waves (SAWs) on layered systems, relatively small focus on the study of a fast isotropic layer on a slow isotropic substrate (fast-on-slow system), both in terms of calculation and experiment. The form of the SAW solution below the cutoff (shear wave velocity of the substrate) is relatively well known. A single surface wave solution exists: it begins at the Rayleigh velocity of the substrate, and increases as the frequency thickness product increases until the cutoff is reached[1]. However, there is little in the literature about the behaviour beyond the cutoff. Bogy and Gracewski[2] and Tsukahara *et al.*[3] considered the problem theoretically by looking for dips in the magnitude of the reflectance function. Chimenti and Nayfeh[4] followed experimentally a mode to a velocity 130% greater than the shear velocity but, in a later paper, did not mention the behaviour beyond the cutoff[5]. The purpose of this paper is to consider the propagation of the SAW near the cutoff for a stiffening surface layer. It is shown that there is an anomaly in the attenuation of the SAW at this point. Existence of this anomalous behaviour has been proven experimentally using acoustic microscopy. To the author's knowledge, this is the first experimental work where the complex dispersion curve has been completed beyond the cutoff for a fast on slow system.

II. SAMPLES AND MODELLING

Measurements and numerical simulation have been made on aluminum coated with a thin and uniform layer of porous anodised oxide (oxalic acid anodised aluminum, see details[6,7]). Porous oxide films are used widely in aircraft industry for increasing the durability of adhesive bonding[8]. Measurements were carried out with an acoustic microscope and a line focus lens at a frequency of 225 MHz. The SAW velocity and its attenuation were extracted from the $V(z)$ curves as described by Kushibiki and Chubachi[9]. Experimental and theoretical $V(z)$ curves are presented in Figs. 1 and 2. Theoretical $V(z)$ curves have been calculated for the cylindrical lens using the following expression:[10]

$$V(z)=\int_0^{\theta_m} P(\theta)^2 R(\theta) e^{-2\,kz\cos\theta} d\theta, \tag{1}$$

here $P(\theta)$ is the pupil function, $R(\theta)$ is the reflection coefficient, k is the wave number in liquid, θ_m is the semiaperture angle of the lens, and z is the defocusing distance. It is accepted in acoustic microscopy that the z axis is directed toward the lens and the SAW are excited only for negative defocus when the virtual focus is located beneath the sample surface (see Figs. 1 and 2). For the $V(z)$ curve simulation, the Gaussian pupil function was used: $P(\theta)=\exp[\log(0.005)(1-\cos\theta)^2/(1-\cos\theta_m)^2]$. The reflection coefficient was calculated using a method described elsewhere[11] with elastic constants from Table I. The SAW velocity V_{SAW} has been derived from the $V(z)$ curves using the well known relationship based on ray considerations[9,12]:

$$V_{\mathrm{SAW}}=\frac{V_W}{\sqrt{1-[1-V_W/(2f\Delta z)]^2}}, \tag{2}$$

where V_W is the speed of sound in water, f is the frequency and Δz is the period of the oscillation of the $V(z)$ curve. The SAW attenuation is related to δ, the exponential decay of the $V(z)$ curve and to α_W, the attenuation due to the propagation in water (see Fig. 3):

$$\alpha=\delta/(2\tan\theta_{\mathrm{SAW}})+\alpha_W/\sin\theta_{\mathrm{SAW}}, \tag{3}$$

where θ_{SAW} is the angle of SAW excitation ($\sin\theta_{\mathrm{SAW}}=V_W/V_{\mathrm{SAW}}$). For the calculations α_W is determined from the expression[13]: $\alpha_W/f^2=2.33\times10^{-15}$ s^2 m^{-1}. In the presentation of the results, the normalised attenuation factor γ is usually used

$$\gamma=\alpha\frac{V_{\mathrm{SAW}}}{2\pi f} \tag{4}$$

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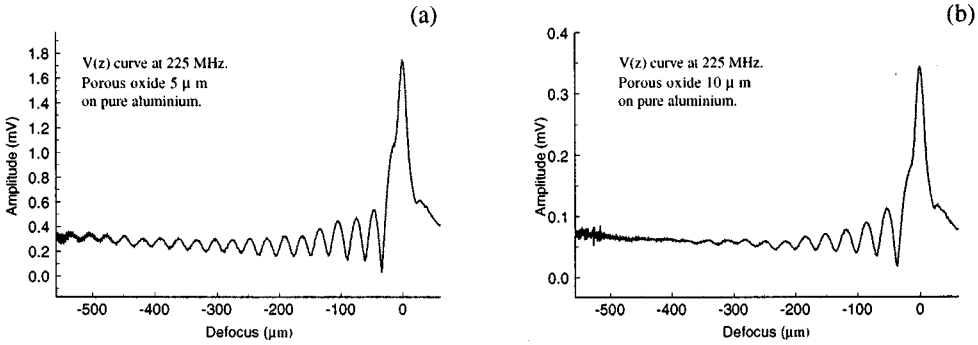


FIG. 1. Experimental $V(z)$ curves for porous oxide on aluminum at 225 MHz. (a) 5 μm thick oxide; (b) 10 μm thick oxide.

III. RESULTS AND DISCUSSION

A. Experimental results

Measured velocities and normalised attenuation factors as a function of the oxide layer thickness are presented in Figs. 4 and 5. Error bars on the experimental points show the scattering of the observed values due to inhomogeneity rather than an error in the measurements at each point. A pronounced dip in the attenuation is revealed (Fig. 5). At the dip, corresponding to a 5 μm thick oxide layer, the $V(z)$ curve exhibits 18 oscillations [Fig. 1(a)], a high number for an experimental $V(z)$ curve; the attenuation measured here is therefore reliable. The value of the surface wave velocity increases from 2.95 km s^{-1} (pure aluminum) to 3.6 km s^{-1} (50 μm of oxide on aluminum). At 225 MHz, a velocity of 3.6 km s^{-1} corresponds to a wavelength of 16 μm, which is smaller than the thickness of the layer. Thus, a 50 μm film can be considered as a half space in terms of SAW propagation. The cutoff is reached when the speed of the surface wave is equal to the shear velocity in aluminum (3.1 km s^{-1}). The solid lines in Figs. 4 and 5 are the theoretical evaluations of the SAW dispersion using the technique proposed by Lowe[14]. To reduce the number of unknown variables, the oxide layer was modelled as isotropic. The longitudinal velocity $\hat{V}_l$ and density $\hat{\rho}$ of the layer have been obtained by measuring the normal incidence reflection coefficient[15] at a frequency of 100 MHz for a sample of a thickness 100 μm (Table I). A value of $\hat{V}_t = 3830$ m s^{-1} for the velocity of the transverse bulk wave was obtained by fitting the experimental dispersion curve (the filled triangles in Fig. 4). The parameters used for aluminum (V_l, V_t, ρ) are presented in Table I.

B. Anomaly near cutoff

The most peculiar aspect of the theoretical curves calculated with constants listed in Table I, is the anomalous behaviour of the attenuation near the cutoff. In contrast to the slow-on-fast system, where only small changes occur[16], for fast-on-slow the attenuation decreases as the velocity approaches the cutoff and sharply increases just above it. A similar behaviour of the attenuation after cutoff can be found in the vacuum - oxide layer - aluminum system; evaluation of the attenuation for this case is shown in Fig. 6. The shape of the dispersion curve is similar to the system with water, but the behaviour of the attenuation is markedly different. Before cutoff, the attenuation is zero, and a true surface wave propagates[1]. Beyond the cutoff, the surface wave becomes a pseudo surface wave, since it radiates energy into aluminum. Passing the cutoff point is associated with a sharp increase in attenuation followed by a decay towards zero. Without water loading (Fig. 6), the position of the cutoff can be defined precisely, being the point on the dispersion curve at which the attenuation starts to grow. For the vacuum-oxide-aluminum system the thickness from which the true SAW becomes a pseudo SAW is equal to 4.4 μm. In the case of water loading, the position of the cutoff point is not defined so clearly. Since the wave leaks energy into the water at all

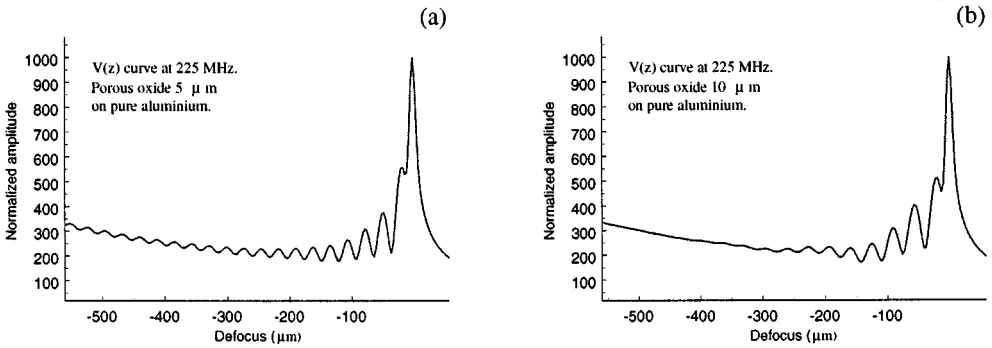


FIG. 2. Theoretical $V(z)$ curves for porous oxide on aluminum at 225 MHz. (a) 5 μm thick oxide; (b) 10 μm thick oxide.

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TABLE I. Materials constants used for numerical simulations.

	ρ (kg m $^{-3}$)	V_l (km s^{-1})	V_t (km s^{-1})
Water	1000	1.483	10^{-5}
Oxide	2480	8.206	3.84
Aluminum	2667	6.396	3.103

frequencies, there is no longer a step change from a nonattenuating wave to an attenuating wave. However, the strong attenuation associated with leakage into the aluminum starts to grow from a thickness of 4.0 μm. This thickness is termed the cutoff thickness for the case of water loading. Nayfeh and Chimenti[5] estimated the thickness at which the cutoff occurs using, a thin layer approximation:

$$h_{cut}=\frac{V_t}{2\pi f}\frac{\hat{\rho}/\rho}{[(\hat{V}_t/V_t)^2-1]\sqrt{1-(V_t/V_l)^2}}. \tag{5}$$

The expression (5) approximate formula gives a cutoff thickness of about 5.2 μm for the water-oxide-aluminum system.

To arrive at an understanding of the anomalous character of the attenuation the direction of the energy leakage is now considered (Fig. 3). Before cutoff (Fig. 3), the surface wave loses energy in the coupling water, it is thus a leaky SAW; after the cutoff point, the surface wave becomes a pseudo-leaky SAW since it radiates energy both into the liquid and the substrate (this is the opposite of the slow-on-fast case, corresponding to the Sezawa waves[16]). Attenuation starts from the value of the leaky SAW attenuation in aluminum (Fig. 5) and then its value decreases with increasing thickness. The SAW attenuation on aluminum due to leaking into the liquid can be described by the approximate expression[17]:

$$\alpha\lambda_w=\frac{\rho_w V_w^2}{\rho V_{\mathrm{SAW}}^2}, \tag{6}$$

where λ_w is the wavelength of sound in the liquid and ρ_w is its density.

Approaching cutoff, the value of the attenuation tends to zero (Fig. 5). The amplitude of the reflection coefficient just below cutoff at thickness $h=3.9$ μm and for the pure substrate (aluminum, $h=0$), are presented in Fig. 7. For aluminum, the amplitude of the reflection coefficient at the Rayleigh angle is equal to 1 (Fig. 7). Just below the cutoff, when the speed of SAW is practically equal to the speed of the shear wave in the substrate, the reflection coefficient has a minimum at an angle of 27.9°. This corresponds to the angle of excitation of SAW ($V_{\mathrm{SAW}}=3.1$ km s^{-1}) for that thickness. Since the magnitude of the amplitude at the dip is small ($|R|=0.16$), almost all energy is transferred into the solid. The minimum in the attenuation and small value of the reflection at the SAW angle can be interpreted as follows. When the SAW is approaching the speed of the shear velocity of the substrate, its structure becomes more close to the structure of the bulk shear wave in the substrate[1]. Therefore, the SAW penetrates more deeply into the substrate and as the energy is spread over a larger space, the amplitude of the oscillations of the particles at the solid -liquid interface decreases; hence, the leakage of the energy back to the liquid also decreases. At the cutoff the SAW tends to the shear lateral wave propagating along the surface.

After the cutoff the SAW starts to radiate energy into the substrate (Fig. 3) and the direction of the leakage is determined by the expression: $\sin\theta_P=\hat{V}_t/V_{\mathrm{SAW}}$, where θ_P is measured from the normal to the surface. Thus just beyond cutoff direction of the leakage is almost parallel to the interface. As thickness and speed of SAW increases, the direction of leak-

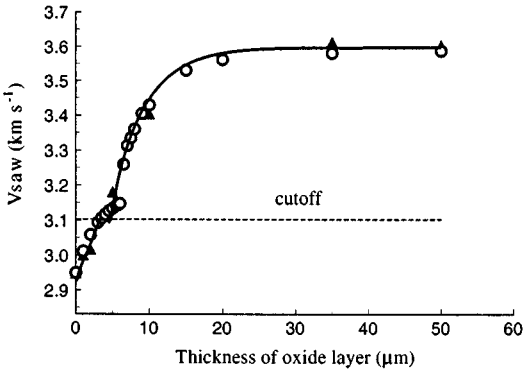


FIG. 4. Dispersion of leaky SAW for a porous oxide film on aluminum. Filled triangles are measurements made by a cylindrical lens at 225 MHz. The solid line is the theoretical prediction. Empty circles were obtained by calculating theoretical $V(z)$ curves.

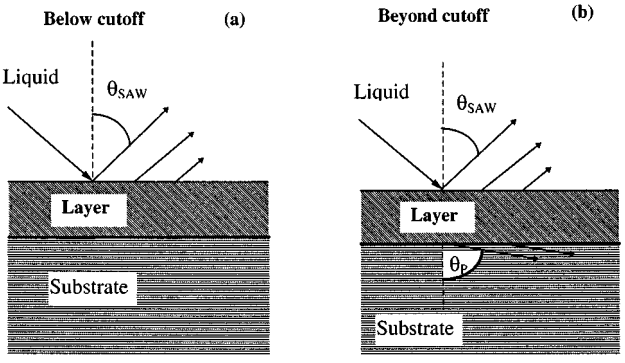


FIG. 3. Schematic drawing of acoustic energy leakage for layered system: (a) below cutoff, (b) beyond cutoff.

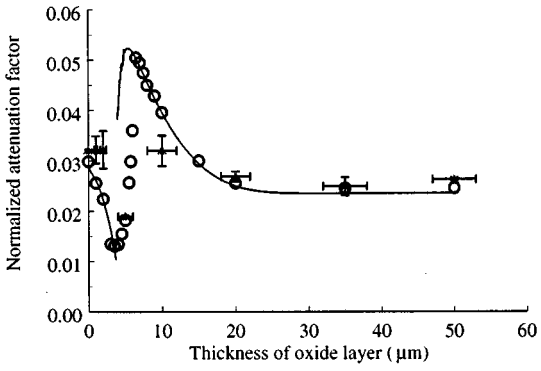


FIG. 5. Attenuation of leaky SAW for porous oxide film on aluminum. Notations are the same as in Fig. 4.

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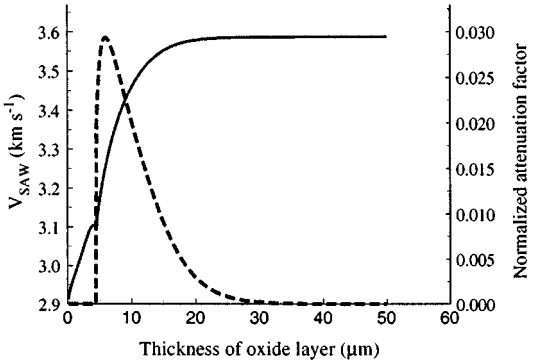


FIG. 6. Dispersion (solid line) and attenuation (dashed line) of leaky SAW for porous oxide film on aluminum at 225 MHz.

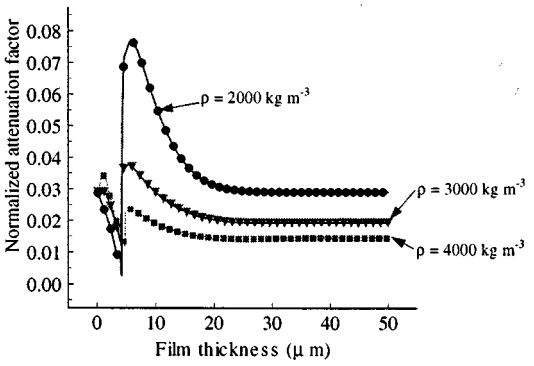


FIG. 8. Influence of the variation of the density of the layer on the jump in attenuation at the cutoff at 225 MHz.

age is inclined further towards the normal and the attenuation increases rapidly. At the same time, with increasing thickness, the energy of the SAW that reaches the interface decreases, since the energy of SAW is concentrated near the top surface of the layer. When the last mechanism becomes dominant, the attenuation starts to decrease. At 225 MHz the attenuation reaches a maximum at a thickness of 5.5 μm. The value of the reflection coefficient at the dip is relatively small (when $h=5.5$, $|R|=0.12$ at an angle of 27.1°), hence almost all energy of the SAW radiates into the substrate.

The attenuation drops to the value of the attenuation of an oxide half space above a thickness of 20 μm, which is thicker than the depth of penetration of the SAW. Thus the SAW becomes a leaky Rayleigh SAW propagating along the oxide-liquid interface. Clearly the behaviour of the attenuation around cutoff must be similar for all kinds of fast layers. This is because the physical mechanisms involved in the transformation of the leaky SAW to a pseudo-leaky SAW described previously are common for all stiffening systems.

The influence of the elastic parameters of the layer on the behaviour of the attenuation near cutoff is now considered. Numerical simulations show that the variation of the longitudinal velocity of the layer does not change behaviour sufficiently near cutoff. The influence of the variation of the density and shear velocity of the layer are presented in Figs. 8 and 9 respectively. Increasing the density leads to the decrease in the attenuation beyond cutoff (for $\hat{\rho}=4000$ kg m^{-3} the jump in the attenuation is fairly small). Decreasing the density results in a strong increase of attenuation above cutoff. For $\hat{\rho}=2000$ kg m^{-3} the attenuation at the maximum reaches the value ($\gamma=0.08$ neper) above which acoustic microscopy measurements are almost impossible[18]. A rise of the shear velocity of the layer causes an increase in the jump in the attenuation around cutoff (Fig. 9). Thus, the high shear velocity (for $\hat{V}_t=5.8$ km s^{-1}, γ at maximum equals to 0.075) can render the SAW after cutoff practically invisible to acoustic microscopy. The high value of the attenuation for a very fast layer such as a diamondlike film is the probable reason for the difficulties of making SAW measurements beyond cutoff[19].

C. Measurements near cutoff

The velocity and attenuation of SAW measured experimentally are in good agreement with theoretical prediction. The one exception is attenuation measured for the sample of 5 μm thickness (see Fig. 5). To understand this discrepancy the behaviour of the $V(z)$ curve around cutoff has been simulated. Using reflection coefficients for different thicknesses of oxalic oxide layer (Fig. 7) calculated using the parameters of Table I, the $V(z)$ curves have been derived using (1) (Fig. 2). The speed and the attenuation were then

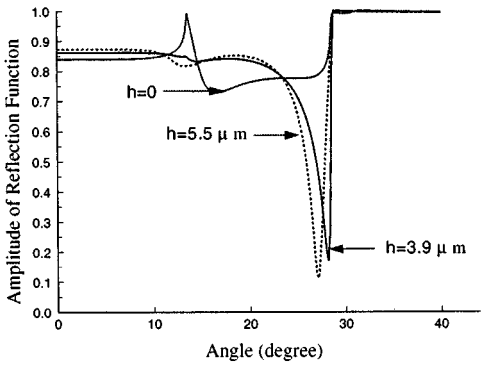


FIG. 7. Magnitude of the reflection coefficient for porous alumina film on aluminum at 225 MHz.

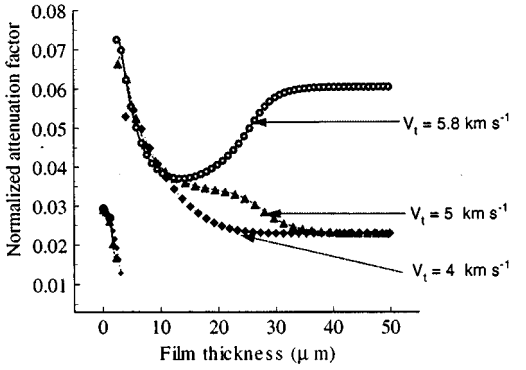


FIG. 9. Influence of the variation of the shear velocity of the layer on the jump in attenuation at the cutoff at 225 MHz.

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obtained with the standard procedure for $V(z)$ curve treatment[9]. The empty circles on Figs. 4, 5 are the values obtained using the reflection coefficient calculations. Two features can be seen clearly in the plots. First, there is no discontinuity near the cutoff, either in the velocity or in the attenuation of the SAW. Second, the behaviour of the attenuation derived via reflection coefficients is smoother than the shape of the attenuation calculated from the dispersion equation beyond cutoff. The same features can be observed in a careful experiment made by Kushibiki *et al.*[16] for the case of a slow-on-fast layer. It means that geometrical optics approach [Eqs. (2) and (3)] does not provide the accurate measurements of the attenuation just after cutoff. However the shape of the attenuation derived through the reflection coefficient below cutoff is in good agreement with that calculated from the dispersion equation. The sharp minimum of the attenuation is still observed and it can be determined using the acoustic microscope.

IV. CONCLUSIONS

An anomalous behaviour of the attenuation near the cutoff has been found for a fast layer on slow substrate. Consideration of the physical phenomena taking place near cutoff showed that this anomaly must be common for a fast-on-slow system. The experiments revealed that a mode is excited well above the shear velocity of the aluminum and tends to the Rayleigh wave on the oxide half space with increasing the thickness of the porous anodised oxide film.

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