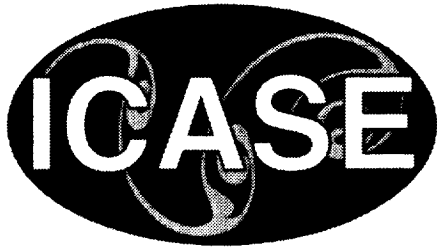


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Common-path Heterodyne Laser-induced Thermal Acoustics for Seedless Laser Velocimetry

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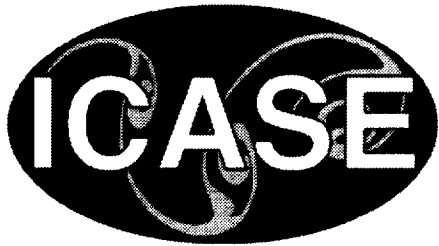
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COMMON-PATH HETERODYNE LASER-INDUCED THERMAL ACOUSTICS FOR SEEDLESS LASER VELOCIMETRY

ROGER C. HART^{*}, G. C. HERRING[†], AND R. JEFFREY BALLA[‡]

Abstract. We demonstrate the use of a novel technique for the detection of heterodyne laser-induced thermal acoustics signals, which allows the construction of a highly stable seedless laser velocimeter. A common-path configuration is combined with quadrature detection to provide flow direction, greatly improve robustness to misalignment and vibration, and give reliable velocity measurement at low flow velocities. Comparison with Pitot tube measurements in the freestream of a windtunnel shows root-mean-square errors of 0.67 m/s over the velocity range 0 – 55 m/s.

Key words. LITA, laser velocimetry, laser anemometry, laser-induced thermal acoustics

Subject classification. Experimental Fluid Dynamics

1. Introduction. Non-intrusive optical methods for measuring fluid flow velocity are of great importance to the experimental fluid dynamics and aerodynamics communities. However, the only optical velocimetry methods to have found wide use, laser doppler velocimetry [1] and particle image velocimetry [2], require the introduction of small ($\sim 1\ \mu\text{m}$ diameter) seed particles into the flow to serve as light scatterers. Seeding is not feasible in some wind tunnels due to concerns over removal of spent seed, clogging of flow-straightening screens, or abrasion of finely polished surfaces. Additionally, there are regions in airflows of interest, such as vortices over delta wings or behind leading-edge slats, where useful seed concentrations are difficult or impossible to achieve. Thus a need exists for a seedless laser velocimetry method. Previous work has demonstrated the potential of laser-induced thermal acoustics (LITA) to fill this need [3-6]. However, none of the approaches employed so far for heterodyne detection appears suitable for routine use in environmentally adverse windtunnel environments by workers who are not highly skilled optics researchers. Here we demonstrate a novel means of implementing LITA velocimetry that has the intrinsic stability and robustness to allow the construction of a useful, fieldable instrument.

2. Theory of LITA Signal Detection. LITA is a pump-probe process: a pump laser creates a periodic perturbation in the medium, which serves to diffract the beam of a probe laser to a detector. In our apparatus the beam of a Q-switched Nd:YAG laser operating at wavelength $\lambda_{\text{pump}} = 1064\ \text{nm}$ is split by a 50/50 beamsplitter to produce two pump beams which are made to focus and cross at a single point at angle $2\theta = 1.4^\circ$ by a lens (Fig. 2.1).

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Interference fringes of period $\Lambda = \lambda_{pump}/2\sin\theta$ are formed at the beam intersection. As the laser wavelength is not resonant with any absorptive transition in the medium (air) the only optical interaction is electrostriction, which creates two counter-propagating acoustic waves or gratings traveling in the $\pm\hat{x}$ direction at speed of sound v_S with respect to the medium. The acoustic wavelength is equal to the optical fringe spacing and the frequency $f_B = v_S/\Lambda$ is about 7.8 MHz at room temperature. The beam of the CW probe laser at wavelength $\lambda_{probe} = 532$ nm

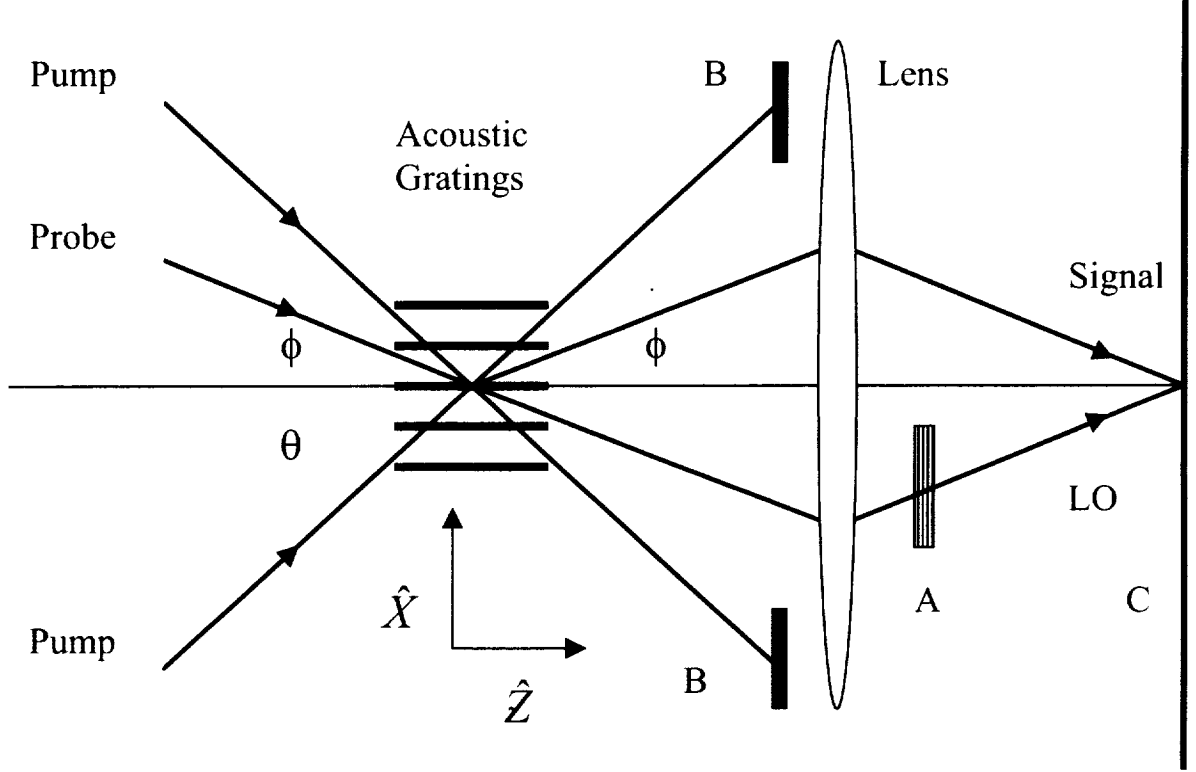


FIG. 2.1. Beam crossing geometry and schematic of detection scheme. A: attenuator; B: beamstop; C: Focal/detector plane; LO: local oscillator beam.

is incident on the waves at the Bragg or phase-matching angle ϕ where $\Lambda = \lambda_{probe}/2\sin\phi$. The signal beam is diffracted at angle ϕ (Fig. 2.1) with Doppler shifts $\Delta\omega_+ = -\vec{q} \cdot (\vec{v}_{con} - \vec{v}_S)$ and $\Delta\omega_- = -\vec{q} \cdot (\vec{v}_{con} + \vec{v}_S)$ due to the motion of the gratings, where \vec{v}_{con} is the flow velocity, $\vec{v}_S = v_S\hat{x}$, and $\vec{q} = q\hat{x}$ is the acoustic grating vector with $q = 2\pi/\Lambda$.

2.1. Collinear Local Oscillator Method. The simplest implementation of LITA velocimetry (not shown) requires the introduction of a local oscillator (LO) beam collinear with the signal with the same frequency ω as the probe. The field is

$$(2.1) \quad A(t) = A_{LO} \exp(i\omega t) + A_S e^{-\beta t} (\exp(i(\omega + \Delta\omega_- t)) + \exp(i(\omega + \Delta\omega_+ t))) + c.c. ,$$

where A_{LO} and A_S are the real amplitudes respectively of the LO and signal beams, $\beta = \alpha v_S$ with α the acoustic amplitude absorption coefficient [7], and *c.c.* means complex conjugate. Averaging over a time long compared to the optical period but short compared to $1/f_B$ and integrating over the area of the beams, the time dependence of the detected power is

$$(2.2) \quad P(t) = A_{LO}^2 + 2A_{LO}A_S e^{-\beta t} [\cos(\Delta\omega_- t) + \cos(\Delta\omega_+ t)],$$

where we assume $A_{LO} \gg A_S$ for shot-noise-limited detection and so neglect the term $\propto A_S^2$. Neglecting also the DC term, the real part $\tilde{P}_R(\tilde{\omega})$ of the Fourier transform of $P(t)$ is a sum of four Lorentzians

$$(2.3) \quad \tilde{P}_R(\tilde{\omega}) = 2A_{LO}A_S \left[\frac{\beta}{\beta^2 + (\tilde{\omega} \pm \Delta\omega_-)^2} + \frac{\beta}{\beta^2 + (\tilde{\omega} \pm \Delta\omega_+)^2} \right],$$

with peaks at $\pm\Delta\omega_-$ and $\pm\Delta\omega_+$. Although the Doppler shifts are signed quantities, the detected heterodyne signal contains information only on the absolute values. Analysis (*e.g.* discrete Fourier transform or time domain fitting via Levenburg-Marquardt or Prony's method [6]) of real-valued data described by Eq. 2.2 thus allows independent determination only of $|\Delta\omega_-|$ and $|\Delta\omega_+|$, yielding v_S and $|v_F|$, where $v_F = \hat{q} \cdot \vec{v}_{con}$ is the component of flow velocity along \hat{q} .

Laboratory evaluation of this collinear LO method of implementing LITA velocimetry [6] revealed the following disadvantages: 1) proper alignment of the LO and signal beams is difficult to achieve and maintain; 2) the apparatus is very sensitive to vibration since the signal and LO beam must follow different paths on different optics; 3) no direct means of determining flow direction is available since only the absolute values of $\Delta\omega_-$ and $\Delta\omega_+$ are available as shown above; 4) both accuracy and precision are very poor for flow velocities less than ~ 20 m/s due to the difficulty of accurately discriminating the nearly degenerate frequencies $|\Delta\omega_-|$ and $|\Delta\omega_+|$ in the presence of noise. Although various technical means of ameliorating these difficulties are available, this approach seemed unsuitable to be the basis of a robust instrument with a useful velocity dynamic range.

2.2. Grating Demodulation with Quadrature Detection. A solution to these four problems was found with two modifications: a non-collinear geometry, and quadrature detection. A lens recrosses and refocuses the signal and attenuated probe beams in plane C (Fig. 2.1.). Assuming for simplicity unit magnification, the field at C is

$$(2.4) \quad A(t) = A_{LO} \exp \left(i \left(\vec{k}_{LO} \cdot \vec{r} - \omega t \right) \right) + A_S e^{-\beta t} \exp \left(i \left(\vec{k}_S \cdot \vec{r} - (\omega + \Delta\omega_-) t \right) \right) + A_S e^{-\beta t} \exp \left(i \left(\vec{k}_S \cdot \vec{r} - (\omega + \Delta\omega_+) t \right) \right) + c.c.,$$

where \vec{k}_{LO} and \vec{k}_S are the wavevectors for LO and signal beams with $|\vec{k}_{LO,S}| = 2\pi/\lambda_{probe}$. With $|\vec{k}_{LO} - \vec{k}_S| = q$ (due to the phase matching between pump and probe), and neglecting the term $\propto A_S^2$, the intensity in plane C is then

$$(2.5) \quad I(x,t) = A_{LO}^2 + 2A_{LO}A_S e^{-\beta t} [\cos(qx + \Delta\omega_- t) + \cos(qx + \Delta\omega_+ t)],$$

which describes interference fringes of spatial period Λ traveling at speeds $\Delta\omega_+/q = v_F - v_s$ and $\Delta\omega_-/q = v_F + v_s$; that is, *the lens produces an image of the acoustic waves*. No modulation at frequencies $\Delta\omega_-$ and $\Delta\omega_+$ would be seen by a broad-area detector (width $\gg \Lambda$) placed at C. However, if a series of slits (e.g. a Ronchi ruling) parallel to the fringes with period $\Lambda = 2D$ is placed on the surface of the detector (Fig. 2.2) the modulation is recovered as bright fringes pass alternately across transparent and opaque regions. We refer to this detection scheme as *grating demodulation*. Taking advantage of the equal periodicities of the fringes and the Ronchi ruling, the time dependence of the detected power $P(t)$ may be written

$$(2.6) \quad P(t) = F \int_a^{a+D} I(x,t) dx$$

where F is a constant accounting for the number of fringes and the height of the beams, and a specifies the transverse location (phase) of the ruling with respect to an arbitrary origin (Fig. 2.2). After some manipulation one finds

$$(2.7) \quad \begin{aligned} P(t) = & bA_{LO}^2 \\ & - 2cA_{LO}A_S e^{-\beta t} (\sin(\varphi)\cos(\Delta\omega_- t) + \cos(\varphi)\sin(\Delta\omega_- t)) \\ & - 2cA_{LO}A_S e^{-\beta t} (\sin(\varphi)\cos(\Delta\omega_+ t) + \cos(\varphi)\sin(\Delta\omega_+ t)), \end{aligned}$$

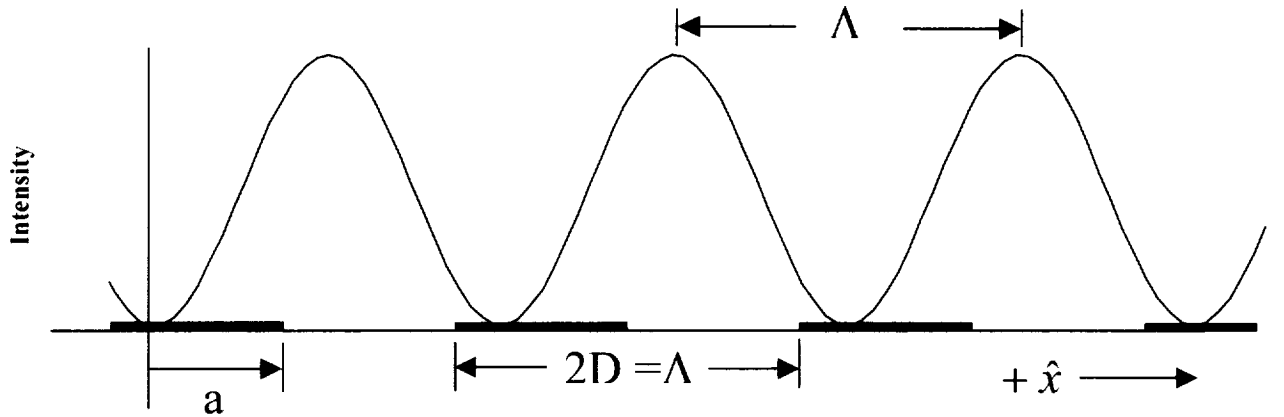


FIG. 2.2. Plane C in Fig. 2.1 showing Ronchi ruling (thick lines) and one traveling fringe pattern.

where $\varphi = \pi a/D$ and b and c are constants. Thus by shifting the ruling transverse to the optical axis (changing a) the phase of the modulation in the signal may be varied; *this is equivalent to shifting the phase of the local oscillator*. This provides a convenient means for implementing dual-channel phase-sensitive detection with two phases of the LO differing by 90° , known as quadrature detection. If the converging signal and LO beams (Fig. 1) are divided by a suitable beamsplitter so that two separate beam intersections are formed on two separate rulings and detectors, then by setting the relative transverse shift between the rulings to $\Lambda/4$ both quadrature components of the signal may be recovered simultaneously. That is, for channel $P_0(t)$ let $a = 3D/2$ in Eq. 2 and for channel $P_{90}(t)$ $a = D$, giving

$$(2.8) \quad \begin{aligned} P_0(t) &= bA_{LO}^2 + 2cA_{LO}A_S e^{-\beta t} (\cos(\Delta\omega_+ t) + \cos(\Delta\omega_- t)), \\ P_{90}(t) &= bA_{LO}^2 + 2cA_{LO}A_S e^{-\beta t} (\sin(\Delta\omega_+ t) + \sin(\Delta\omega_- t)). \end{aligned}$$

Forming the complex signal $Z(t) = P_0(t) + iP_{90}(t)$, we find the real part of the Fourier transform now consists of only two Lorentzians

$$(2.9) \quad \tilde{Z}_R(\tilde{\omega}) = 2cA_{LO}A_S \left[\frac{\beta}{\beta^2 + (\tilde{\omega} - \Delta\omega_+)^2} + \frac{\beta}{\beta^2 + (\tilde{\omega} - \Delta\omega_-)^2} \right]$$

with peaks at $\Delta\omega_+$ and $\Delta\omega_-$. Thus analysis of $Z(t)$ can recover the sign as well as magnitude of the Doppler shifts (Fig. 2.3). For $v_F = 0$ the spectral peaks occur at $\tilde{\omega} = \pm qv_S = \pm\omega_B = \pm 2\pi f_B$; as v_F varies the peaks will shift simultaneously towards more positive or more negative frequency (depending on the flow direction) but will maintain the separation $2\omega_B$. Flow and sound velocities are found as $v_F = (\Delta\omega_+ + \Delta\omega_-)/2q$ and $v_S = (\Delta\omega_+ - \Delta\omega_-)/2q$. Note that Mach number $M = v_F/v_S$ is independent of q , so if flow temperature and thus

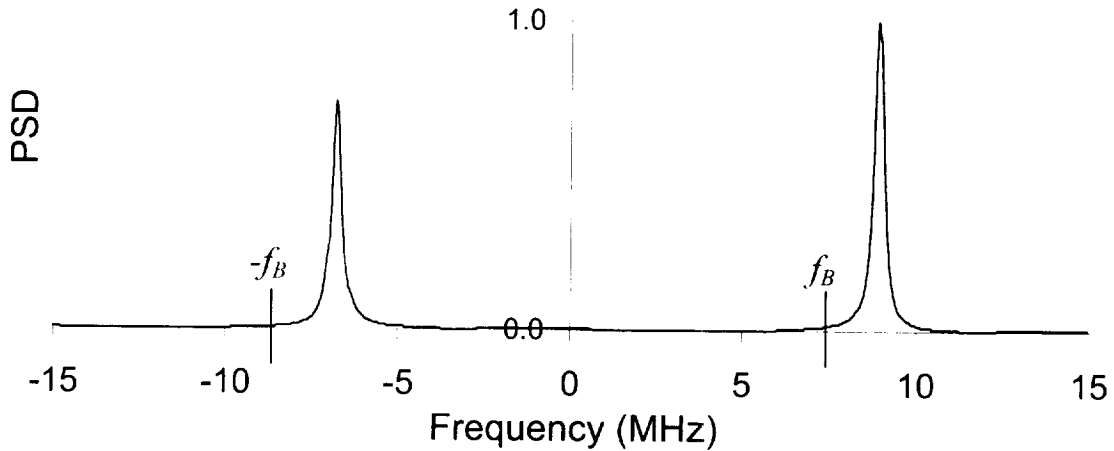


FIG. 2.3. Experimental power spectral density (PSD) of single-shot LITA waveform taken using grating demodulation and quadrature detection. Flow velocity $v_F = 45$ m/s, and $f_B = 7.8$ MHz.

v_S are known v_F may be found without calibration of Λ .

This grating demodulation/quadrature detection scheme remedies the defects found in the collinear LO method. Since signal and LO beams are incident on the same optics (common path), detection is *intrinsically* stable against both misalignment and vibration. Flow direction is found directly. Resolution at low velocities is greatly improved since the frequencies $\Delta\omega_-$ and $\Delta\omega_+$ are no longer nearly degenerate.

3. Experimental Results. A compact velocimeter employing this detection scheme was used at NASA Langley Research Center's Basic Aerodynamics Research Tunnel to map the flow behind a rearward-facing step [8]. As part of this program, multiple comparisons of freestream velocity V_{LITA} (average of ~ 350 shots) measured by LITA with freestream velocity V_{Pitot} measured by Pitot tube were acquired (Fig. 3.1). Defining error as $V_{Pitot} - V_{LITA}$, the root-mean-square error (RMSE) of this data set is 0.67 m/s. For $V_{Pitot} > 30$ m/s and for $V_{Pitot} = 0$, the RMSE is < 0.4 m/s, while for intermediate velocities RMSE is 0.84 m/s. Note that a velocity of 1 m/s corresponds here to a Doppler shift of 23 kHz in a carrier frequency of 5.6×10^{14} Hz.

We have demonstrated an elegant, intrinsically stable means of performing heterodyne LITA velocimetry with quadrature detection that will allow the construction of a robust seedless laser velocimeter.

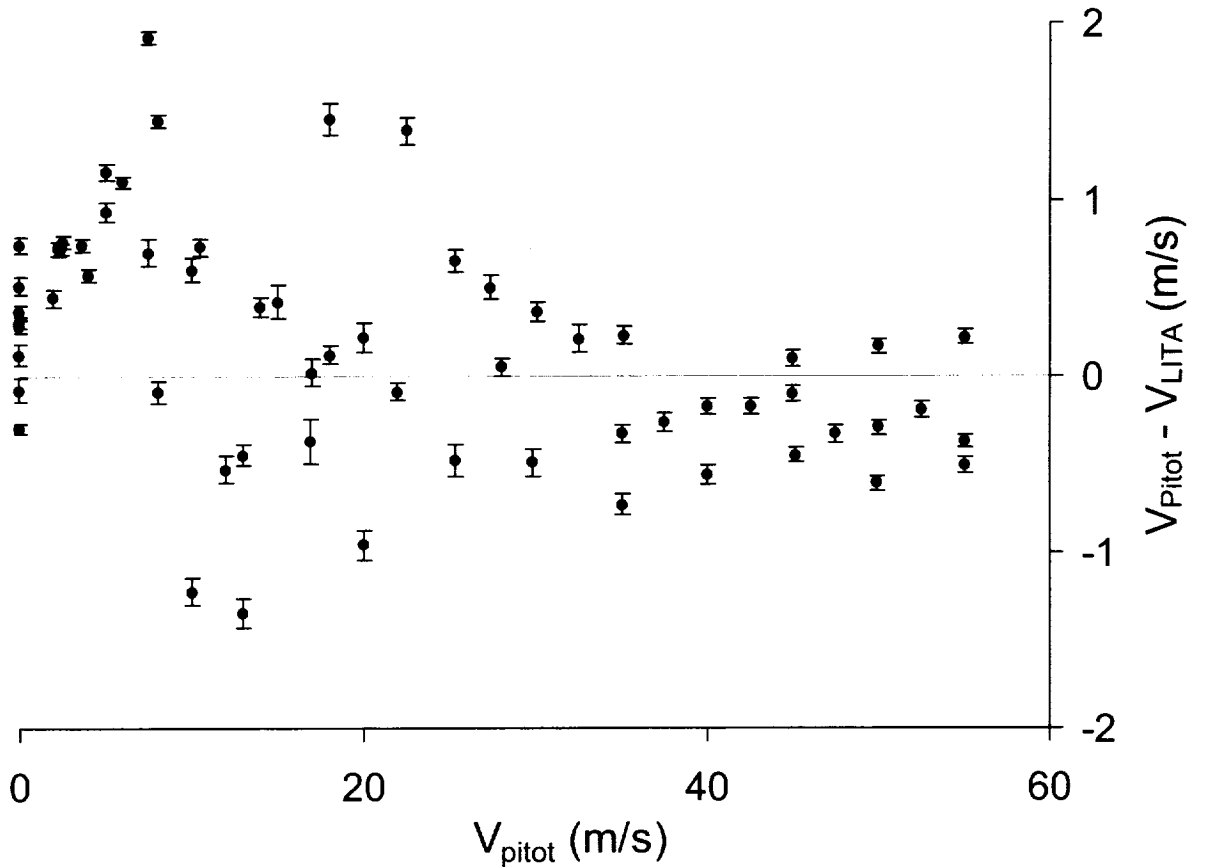


FIG. 3.1. Error $V_{Pitot} - V_{LITA}$ for measurements in windtunnel freestream. Error bars show one standard deviation of the mean.

We wish to acknowledge the invaluable assistance of Mark Fletcher and Luther Jenkins in carrying out the windtunnel measurements.

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