(NASA-CR-147144) DIRECTIONAL ACOUSTIC MEASUREMENTS BY LASER DOPPLER VELOCIMETERS (Arkansas Univ.) 13 p HC $3.50 CSCL 20E
N76-22529
Unclas
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Directional Acoustic Measurements by Laser Doppler Velocimeters*

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Abstract

Laser Doppler velocimeters (LDVs) are used as velocity microphones to measure sound pressure level in the range of 90-130 dB, spectral components, and two-point correlation functions for acoustic noise source identification. Close agreement between LDV and microphone data is observed. Directional sensitivity and the ability to measure remotely make LDVs useful tools for acoustic measurement where placement of any physical probe is difficult or undesirable, as in the diagnosis of jet noise.

An optical velocity microphone has been developed for making remote, noncontact acoustic measurements. Laser Doppler velocimeters[1] (LDVs) are used to determine the acoustic particle velocity from the velocity of tracer particles suspended in the fluid medium. Sound pressure level, directional characteristics, and spectral components are derived from the particle velocity measurements and cross-correlation analysis. Thus, a quantitative description of a noise field can be obtained without any perturbation.

In recent years, noise control has become an important facet of jet engine design.[2-5] Generally, pressure microphones are used to diagnose jet noise despite their several disadvantages: (1) a microphone in a flow field generates wind noise,[6] (2) a microphone may become contaminated, (3) a two-microphone correlation system has poor directional sensitivity for a narrow-band noise source, and (4) the steering mechanisms for microphones are cumbersome. These drawbacks and the often limited access for probe placement in jet noise fields make remote measurement techniques highly desirable.

A pressure microphone responds to instantaneous sound pressure [p(t)]. In a far field, the instantaneous acoustic particle velocity [u(t)] is related to p(t) by[7]

$$u(t) = p(t)/\rho_0 c, \qquad (1)$$

where the product of the density of the fluid medium (ρ_0) and the speed of sound (c) is the acoustic impedance of the fluid medium. If the fluid medium contains tracer particles having a relaxation time τ_p and if the medium is subjected to a sinusoidal excitation of angular frequency ω (that is, $u(t) = U_o \sin\omega t$), then the velocity of the tracer particle $[v_p(t)]$ will be related to $u(t)$ by[8]

$$v_p(t) = u(t)/(1 + \omega^2\tau_p{}^2)^{1/2}. \tag{2}$$

If $u(t)$ is measured by an LDV and $p(t)$ by a microphone, the LDV-measured values of sound pressure level (SPL) and frequency spectrum $[S(\omega)]$ should agree with the corresponding microphone measurements in the audio frequency range. At higher frequencies, reflection from the microphone alters the acoustic field, and corrections must be made to obtain the actual free-field SPL. An LDV can be operated in the ultrasonic frequency range without any significant perturbation. The upper frequency limit is determined only by the response of the tracer particles. From equation (2), if $\omega\tau_p \ll 1$, the acoustic particle velocity can be determined from the velocity of the tracer particles with high fidelity.

In a frequency-biased LDV,[9] the direction of velocity measurement is determined by the geometry of the transmission optics. As shown at either point A or B in Figure 1, the direction of velocity measurement is along the perpendicular to the bisector of the angle θ subtended by the two intersecting laser beams of the LDV. If ϕ is the angle between the direction of travel of the acoustic wave and the direction of velocity measurement and if $v_p(t) \approx u(t)$, then the instantaneous frequency of the LDV signal is given by

$$f(t) = f_c + [2u(t) \cos\phi \sin(\theta/2)]/\lambda, \tag{3}$$

where λ is the wavelength of laser radiation and f_c is the difference in frequency of the two incident laser beams. The demodulated LDV output is proportional to u(t), and the rms value and spectral components of the output can be used to obtain SPL and $S(\omega)$.

Because of the $\cos\phi$ directional response of an LDV, the direction of propagation of the acoustic wave can be readily determined in a free-field condition. However, in the presence of multiple, incoherent noise sources or fluid turbulence, location of individual noise sources is not possible with a single LDV. Under such conditions it is necessary to use a two-LDV correlator, which is similar to a two-microphone correlator.[2,6] If simultaneous measurements are made at points A and B (Figure 1) with a two-LDV correlator, the cross-correlation function $R_{AB}(\tau)$ between the two LDV outputs can be written as

$$R_{AB}(\tau) = (1/T) \int_0^T u_A(t)u_B(t + \tau)dt, \quad (4)$$

where τ is the time delay introduced in one signal with respect to the other, T is the integration time, and $u_A(t)$ and $u_B(t)$ are the particle velocities measured at the points A and B. For a wideband noise source located at S with source-to-receiver distances SA and SB, the correlation function $R_{AB}(\tau)$ will have a peak at $\tau = \tau_o$, where

$$\tau_o = (SB - SA)/c. \quad (5)$$

The value of $R_{AB}(\tau_o)$ will be maximum when $\phi_A = \phi_B = 0^o$. Thus, by steering ϕ_A and ϕ_B, the noise source can be located.

Figure 2 shows the experimental arrangement for LDV measurement of acoustic particle velocity at positions A and B inside an anechoic chamber. A loudspeaker at S was used as the source of acoustic radiation. Acoustic measurements were made with LDVs, using aerosol with a concentration of 10^5 particles/cc, and later with two B&K Type 4136 microphones replacing the LDVs. The SPL was varied from 90 to 130 dB and the acoustic radiation frequency from 500 Hz to 50 kHz. In the audio frequency range, the LDV measurements of SPL, $S(\omega)$, and $R_{AB}(\tau)$ agreed well with the microphone measurements. Figure 3 is a typical plot of $R_{AB}(\tau)$ versus τ for the two-LDV correlation system with $\phi_A = \phi_B = 0^o$ and with the loudspeaker driven by a 4.2 kHz sinusoidal signal. The corresponding plot for the two-microphone correlation system is shown in broken line.

The loudspeaker was then driven with noise having a frequency spectrum of 2-8 kHz. The noise driving the loudspeaker was correlated with the output of the LDV positioned at A, giving a plot of $R_{SA}(\tau)$. Figure 4 shows a comparison of the outputs of the LDV correlator (solid line) and the microphone correlator (broken line). The time delay τ_o for the peak value of $R_{SA}(\tau)$ is the propagation time for the acoustic wave from S to A.

The spatial resolution of LDV measurements is determined by the sensing volume, which is typically 10^{-4} cc with linear dimensions much smaller than the smallest wavelength of acoustic radiation generally involved in aerodynamic noise spectra.[10,11] The LDV signal is generated only when a tracer particle crosses its sensing volume, producing Doppler-shifted, Mie-scattered radiation. In jet-noise studies, the scattering aerosol will be present in the jet exhaust, and artificial seeding may not be necessary. In the present experiments, aerosol containing droplets of dioctylphthalate (DOP) of 0.5-μm count median diameter was used. The particles responded to acoustic excitation with 98 percent fidelity up to an acoustic frequency of 50 kHz.[12]

These experimental studies show that LDVs can be used for acoustic measurement in a wide range of intensity levels and frequency spectra and that two-LDV correlators can be used to identify acoustic noise sources. The advantages are: (1) directional response; (2) high spatial resolution; (3) remote, noncontact measurement unaffected by changes in ambient conditions, such as temperature, humidity, or the presence of corrosive substances; (4) no wind-noise generation; and (5) no apparent upper limit to SPL measurement. The method has potential for use in diagnosis of noise sources in jets and other high-power engines. Other applications may include the determination of the velocity of surface acoustic waves.

The authors are thankful to B. Ragent and W. Ahtye of NASA-Ames Research Center for suggesting this problem, to K. J. Kirsch for his assistance in the experimental studies, and to P. C. McLeod and A. Higgins for helpful discussions.

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*This work was supported in part by the National Aeronautics and Space Administration, Grant No. NGL-04-001-007.

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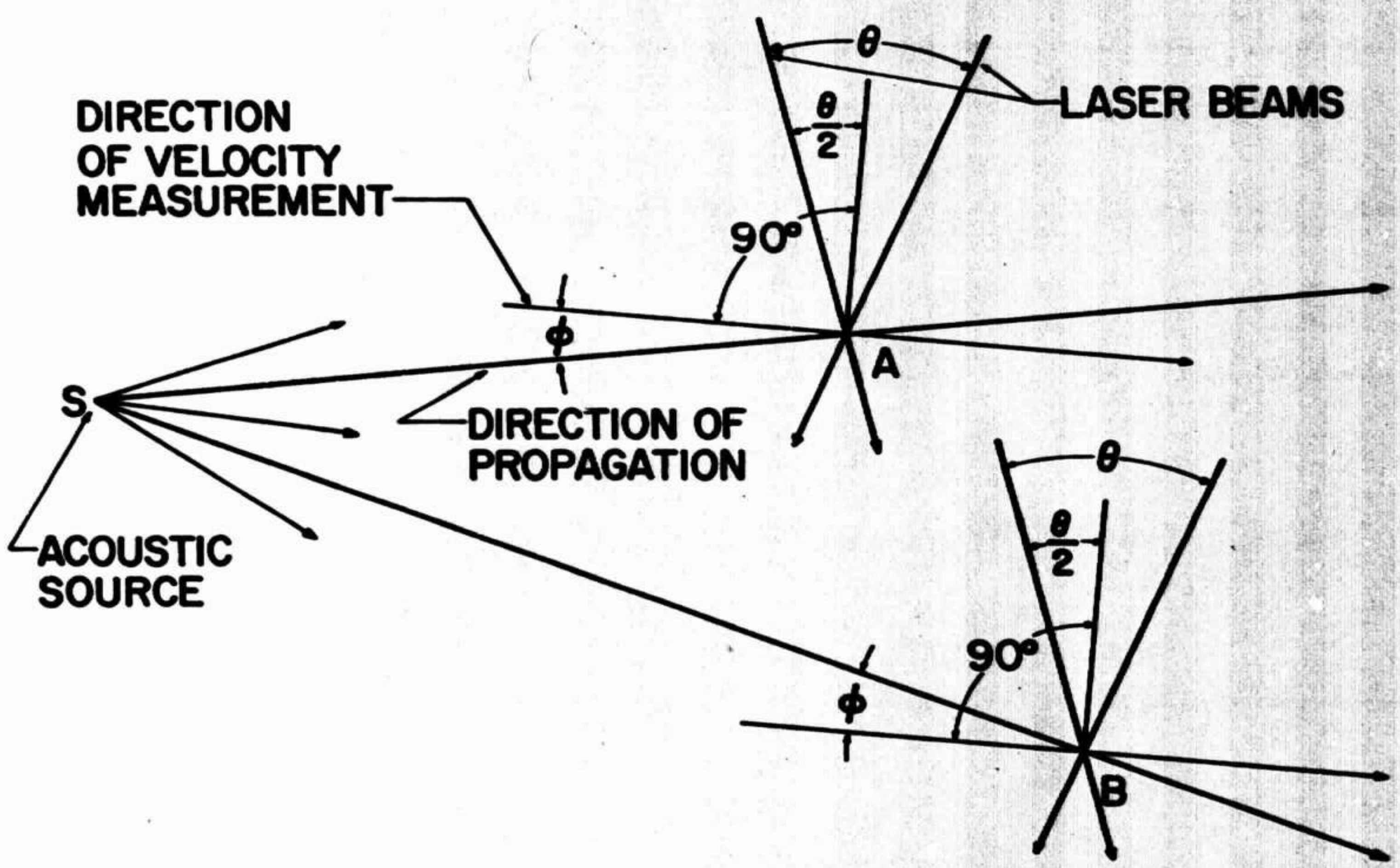
FIGURE CAPTIONS

FIG. 1. LDV beam geometry for acoustic measurements and noise source location. The sensing volumes, A and B, are defined by the intersection of the two laser beams of each LDV. For simplicity, the points S, A, and B and the laser beams are shown as coplanar.

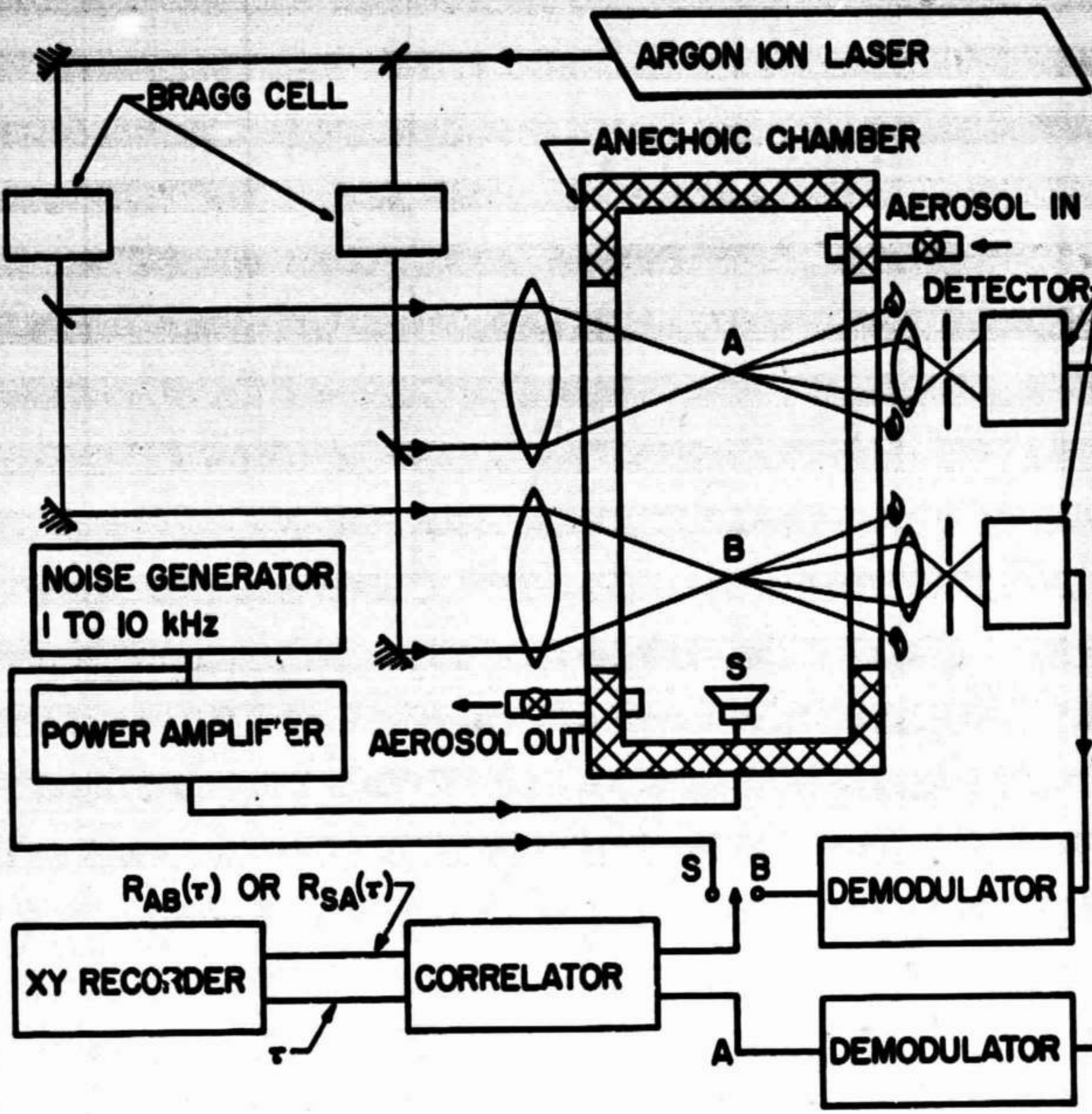
FIG. 2. Experimental arrangement of a two-LDV correlator for acoustic measurements and noise source location.

FIG. 3. Normalized cross-correlation plots obtained by a two-LDV correlator (solid line) and a two-microphone correlator (broken line) are superimposed to show agreement between LDV and microphone measurements in a 4.2-kHz sinusoidal acoustic field.

FIG. 4. Normalized cross-correlation plot obtained between a noise source at S and an LDV at A (solid line) is superimposed over a similar plot obtained between the noise source at S and a microphone at A (broken line). Both methods yield τ_0; but the LDV, being directional, can identify the direction of propagation.



DIRECTION
OF VELOCITY
MEASUREMENT
LASER BEAMS
θ
θ/2
90°
φ
A
S
DIRECTION OF
PROPAGATION
ACOUSTIC
SOURCE
B


ARGON ION LASER
BRAGG CELL
ANECHOIC CHAMBER
AEROSOL IN
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A
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I TO IO kHz
POWER AMPLIF'ER
AEROSOL OUT
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B
$R_{AB}(\tau)$ OR $R_{SA}(\tau)$
DEMODULATOR
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CORRELATOR
τ
A
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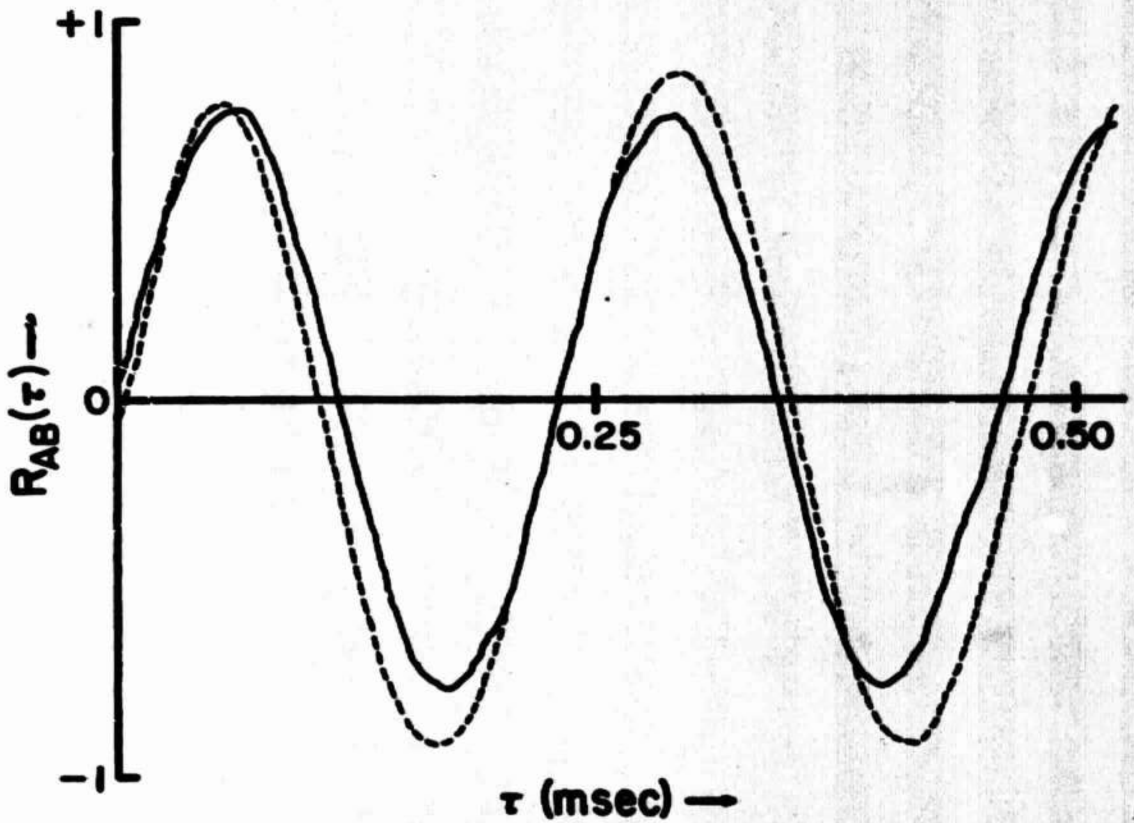
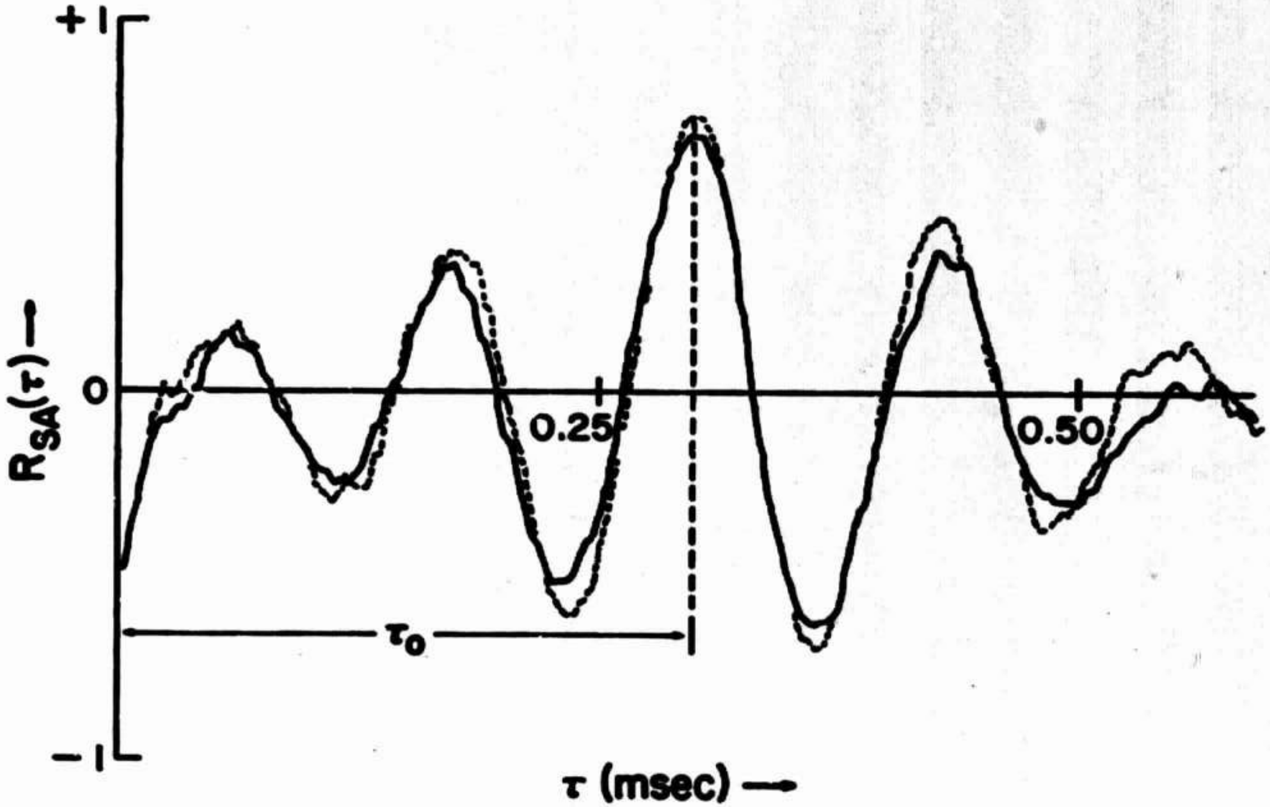


+1
0
-1
$R_{AB}(\tau)$ →
0.25
0.50
τ (msec) →


+1
0
−1
RSA(τ) →
0.25
0.50
τ0
τ (msec) →