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PATTERN SYNTHESIS USING RANDOM ARRAY ELEMENT WEIGHTS

K. Ramya[1], G. S. N Raju[2], P. A. Sunny Dayal[3]

[1, 2, 3] Department of Electronics and Communication Engineering.
Centurion University of Technology and Management, Andhra Pradesh.

Email: [1]kramya@cutmap.ac.in, [2]profrajugsn@gmail.com, [3]sunnydayal@cutmap.ac.in

Corresponding Author: **K. Ramya**

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Abstract

It is well known that methods of pattern synthesis reported in the open literature are mostly conventional. The methods include either standard distribution, empirical techniques, or analytical techniques. Every method has its own advantages and disadvantages regarding the overall pattern structure. The pattern structure is characterized by the main lobe and the side lobe behavior in the case of the sum pattern. On the other hand, difference patterns are the patterns characterized by the two different lobes and side lobe structures. Sequentially generating sum and difference patterns is advantageous in IFF radar applications. To simplify the design procedure and improve the pattern characteristics, an attempt is made to use random weights as amplitude excitation.

Interestingly, useful results are obtained. The sum and difference are designed using the random approach and are presented in the sinθ domain for the arrays of dipoles and microstrip elements. The results are helpful for the array design depending on the applications and user requirements.

Keywords: Antenna array, difference pattern, pattern synthesis, sector beam, sum pattern.

I. Introduction

An antenna is the backbone of any wireless communication system. It should be capable of radiating effectively in the desired direction [V]. The type of antenna selected for specific applications depends on the antenna parameters like directivity, gain, size of the antenna, pattern shape, and side lobe level of the pattern [VII]. The combination of two or more antenna elements is called an array [X]. It has more advantages than a single element. It provides several parameters to control. Therefore, the required pattern shape can be achieved with a specified side lobe level, improved gain, and directivity. The parameters that can be controlled are the geometries of individual elements, excitations (amplitude and phase), and position of each element [II]. The desired pattern is formed by constructive summing of each element pattern of the array in the required direction and destructive summing of every element pattern in unwanted directions, such that minimum Side Lobe Level (SLL) can be achieved [VI].

Side lobes cause the degradation of the required signal; reducing the side lobe level without broadening the main beam is an important problem in communication system applications. The process of controlling any of the mentioned parameters or combinations of parameters for achieving the required pattern with minimum SLL is called pattern synthesis [III].

Designing a Linear Array Antenna is simple; it is the most used array and subject of interest in open literature [II]. The pattern synthesis methods to adjust the amplitude excitations/weights of the array are standard amplitude distributions (SAD), analytical techniques, and empirical techniques. Some standard amplitude distribution methods are uniform AD, circular AD, parabolic AD, cosinusoidal AD, triangular AD, raised cosinusoidal AD, etc. If the same amplitude is given to each element of the array, it is referred to as uniform amplitude distribution, and its first SLL is approximately -13.28 dB [VIII]. If the amplitude of the array elements is circularly distributed along the length of the array, it is called circular amplitude distribution; its first SLL is -17.5 db. If the amplitude variation of the array elements is parabolic, it is called parabolic amplitude distribution; its first SLL is -22 db. If the amplitude variation is along the length of the array with a cosine function, it is called cosinusoidal amplitude distribution; its first SLL is -23.5 db. If the element-to-element amplitude variation along the array is triangular, it is called triangular amplitude distribution, and its first SLL is -26.8 db. If the amplitude of the array varies in a raised cosine shape, it is called a raised cosinusoidal amplitude distribution, and its first SLL is -32 db. The sidelobe level decreases from one distribution to another at the cost of increasing the main lobe beamwidth.

The empirical method is the experimental and computational method, which means that measurements are conducted using the measured values for each physical design, and a redesign will be made. This method can be used to determine both element positions and element excitations to obtain optimum array performance compared to conventional analytical methods [IV]. However, this method is very time-consuming and laborious and requires multiple sets of measured values until the optimal design is achieved.

The literature also reports iterative methods for pattern synthesis. This method sets an initial value for each parameter under control, and increments are repeated until the desired pattern is achieved. Most often, convergence is a significant problem with this method.

The dynamic programming method also makes it possible to synthesize patterns. It involves both mathematical and computer programming methods. It applies to time-varying aspects of problems and is used to solve complex problems effectively.

Perturbation techniques are also reported for pattern synthesis. These are analytical methods for determining approximate solutions of non-linear equations for which exact solutions cannot be obtained. However, they are helpful for the demonstration and prediction of pattern behaviors.

Finite Element Method (FEM), Finite Difference Method (FDM), and Method of Moments (MOM) are also used by some of the researchers for optimization. FEM is very useful for solving problems containing Partial Differential Equations by approximating with numerical model equations, and solutions can be obtained by equation method or matrix method.

FDM is a technique useful for solving the spatial distribution of electromagnetic fields. This method divides the domain into discrete points to obtain the solution. This method is approximate, and errors can be reduced by taking more discrete points.

MOM is an incremental numerical technique that reduces integral equations to linear algebraic equations [IX]. It is helpful to find an integrand from the integral equation, which is known as an integral equation if the integrand is unknown.

Some analytical pattern synthesis methods are the Schelkunoff Polynomial, Fourier Transform, Woodward, Binomial, Dolph-Tschebysheff, Taylor's method, etc [VIII]. Each method is developed to improve the specific characteristics of the radiation pattern at the cost of degrading another parameter [I]. Schelkunoff Polynomial method is developed to produce the nulls in the specified directions. However, there is no control over SLL, which limits the practical use of the array as high SLL causes interference in communication [XI]. The Fourier Transform method is developed to produce the desired pattern. The Woodward-Lawson method is simple and very useful in producing the desired beam shape, but there is no control over the SLL in the trade-off region [VIII]. The binomial array is used in applications where no side lobes are entertained, but the disadvantage is that the main beam width is large [VIII, XI]. There is a trade-off between SLL and main lobe width. Dolph-Tsch-ebysheff method can produce satisfactory patterns with the narrowest beam width for a specified SLL [XI]. Taylor's method produces minimum main lobe width with a specified SLL of equal level, and the amplitude excitation is not largely tapered; hence, it is a practically used method [VIII]. In all these methods, improving one parameter affects the other parameter and has many nonlinear constraints, such that non-linear optimization algorithms must address these constraints. Using stochastic/ evolutionary methods is useful in dealing with constraints that are difficult to deal with by analytical methods. The advantages of stochastic methods are that they give many optimization parameters to control, require less computational time, and allow for comparatively easy implementation of algorithms on computers [III]. In general, stochastic algorithms are of two types: heuristic and metaheuristic. Heuristic means to discover or to find by the trial-and-error process. Further development of heuristic is metaheuristic. Meta means beyond or higher; usually, these algorithms perform better than simple heuristic algorithms. However, in recent days, all stochastic algorithms with local search and randomization have been named metaheuristic algorithms [XIII].

Currently, a lot of research work is being carried out on pattern synthesis of antenna arrays using different optimization methods. Some unconventional stochastic or metaheuristic optimization methods are Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), Ant Colony Optimization (ACO), Flower Pollination Algorithm (FPA), Firefly Algorithm (FA), Taguchi Optimization, Tabu Search Optimization, etc [III]. GA works based on natural selection of biological systems using genetic operators: crossover, mutation, and selection of the fittest. It is more successful in solving a broad range of problems. Hence, it has been a more popular algorithm for many years [XIII]. PSO is one of the most attractive techniques. It was developed based on the swarm intelligence of birds or fish. Individual agents in the search space are called particles; each particle attracts toward the position of the current global best particle or its own best position in the previous history, and it also tends to move randomly [VIII]. SA is based on a trajectory search algorithm. It starts with an initial guess solution at a high temperature and slowly cools down the system. A better move or solution is accepted with a probability. The global optimum solution can be achieved if the system is cooled down slowly [XIII]. ACO is a swarm intelligence algorithm developed by the behavior of ants in a colony. The chemical Pheromone released by each ant is the messenger among ants, evaporating gradually with time. The best route is selected according to the pheromone concentration in the path. FPA is developed based on the pollination process of flower plants. In the global pollination process, pollen is carried by pollinators; pollinators are nothing but insects, and for local pollination, a self-pollination process is used [XII]. FA is also developed based on swarm intelligence. It is inspired by the flashing light characteristics of fireflies. The movement of each firefly is towards the brightest firefly [X].

However, the number of algorithms available in open literature makes it difficult to choose the most suitable algorithm. There are so many choices, and selecting the right optimization technique for the given problem is a difficult task for the designer. Though there are no specific guidelines for selecting algorithms, there are some instructions on what kind of problems can be solved by an algorithm and how to use the algorithm. In all the synthesis techniques, there is a compromise between the antenna pattern parameters. Still, decision-making depends partly on the designer's experience or partly on the trial-and-error process [XIII].

In the present work, to achieve the required pattern characteristics, an attempt is made to decide the amplitude weights of each array element using a random amplitude distribution process. In the digital age of technology, computation time is minimal, and the amount of memory available is vast. For these reasons, the method of randomness is taken into account with the idea of optimizing the radiation patterns. The randomness can be applied to estimate the amplitude or phase of array elements or spacing between the elements. In the present work, amplitude distribution is estimated randomly, and the different patterns for both ideal practical antenna arrays are simulated. Such patterns are sum patterns, difference patterns, and sector beams. The sum pattern is the pattern that consists of maximum radiation in the boresight direction, which is called the main lobe, and minimum radiation in other directions, which are called minor lobes or side lobes. The difference pattern consists of a deep null in the boresight direction, and two major lobes with equal height exist on either side of the null. Instead of steering a narrow beam multiple times, the difference patterns and broad beams are helpful in moving target detection. The broad or sector beam can be generated by introducing phase distribution to the array elements.

II. Random Amplitude Distribution Method

In this, the amplitude/excitation weights are decided by a trial-and-error process, and these are normalized to vary between 0 and 1. Generally, the excitations are symmetric from the center of the array. The following steps are involved in the random amplitude distribution process.

1. Initialize the random value as the amplitude of the first element of the array.

2. Assign the random amplitude value to the second element, which must be less than the first element's amplitude value.
3. Assign the random value as the amplitude of the third element, which should be greater than the second element's amplitude value.
4. Like the above-mentioned steps, all the amplitudes of array elements should be assigned randomly in the sequence. If one element's amplitude is large, the next element's amplitude must be smaller than the previous one, and vice versa.
5. Check the pattern characteristics; if they meet the criteria, stop changing the amplitudes of the elements and take the required pattern.
6. Otherwise, repeat the steps 1 to 5.

III. Formulation

A linear antenna array is one of the simple and commonly used arrays [V]. In the present work, a linear antenna array is considered, in which all the elements are identical, symmetrically placed respective to the origin, and equally spaced using the Ishimaru spacing formula. The problem considered is reducing SLL using amplitude control of individual array elements. Figure 1 shows the even number of isotropic elements arranged from -1 to 1.

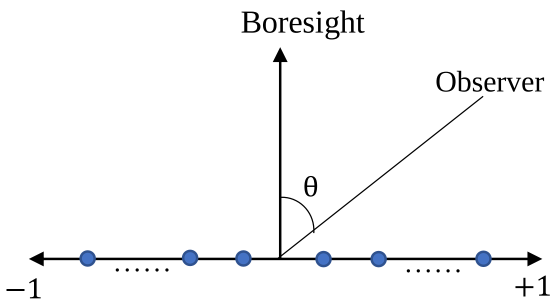

Fig. 1. Geometry of N element symmetric linear array

The total field of an identical array is the field of a single element multiplied by a factor called an array factor [VIII]. The total electric field equation is given as

$$E(\theta, \Phi) = F(\theta, \Phi) \sum_{n=1}^{N} A(x_n) e^{j\frac{2\pi}{\lambda}L[ux_n + \Phi(x_n)]} \tag{1}$$

Where $F(\theta, \Phi)$ Denotes single element field, N represents the number of elements in the array, $A(x_n)$, $\Phi(x_n)$, x_n are excitation of amplitude, phase, and location of n^{th} element respectively, $2L/\lambda$ denotes the normalized length of the array, $u = \sin\theta$ and θ is the angle of the line of an observer with broadside.

The difference patterns are generated from the array equation (1) by introducing a 180-degree phase shift to one-half of the array.

$$E_d(u) = \left[\sum_{n=1}^{\frac{N}{2}} A(x_n) e^{j(2\pi L/\lambda[ux_n + \Phi(x_n)])} dx + \sum_{n=\frac{N}{2}+1}^{N} A(x_n) e^{j((2\pi L/\lambda[ux_n + \Phi(x_n)] + \pi))} dx \right] \quad (2)$$

In the present work, amplitude-only control, as well as both amplitude and phase control, are implemented. The phase distribution $\Phi(x_n)$ is given by

$$\Phi'(x_n) = \frac{1}{(u_2 - u_1)} \int_{-1}^{1} A^2(x_n)\, dx + (u_2 - u_1) \frac{\int_1^x A^2(x_n)\, dx}{\int_{-1}^{1} A^2(x_n)\, dx} \quad (3)$$

$u_2 - u_1$ denotes the desired sectorial beam width, and in the above expression $A(x_n)$ is determined from the random amplitude distribution method.

For amplitude-only control, $\Phi(x_n)$ is 0, then equation (1) becomes (4)

$$E(\theta, \Phi) = F(\theta, \Phi) \sum_{n=1}^{N} A(x_n) e^{j\frac{2\pi}{\lambda} L[ux_n]} \quad (4)$$

In the present work, isotropic elements, half-wave dipole elements, and microstrip patch antenna elements are considered, the element pattern equation for half-wave dipole is given by

$$F(\theta, \Phi) = E_\theta = \frac{j\eta I_m}{2\pi r} e^{-jKr} \left[\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta} \right] \quad (5)$$

where $\eta = 120\pi$, I_m, K and r denotes the maximum current distribution of the element wave number and approximate distance from the dipole element to the observer, respectively.

The element field components of the microstrip patch are given by

$$E_\theta = \frac{\sin\left(\frac{KW \sin\theta \sin\Phi}{2}\right)}{\left(\frac{KW \sin\theta \sin\Phi}{2}\right)} \cos\left(\frac{KL}{2} \sin\theta \cos\Phi\right) \cos\Phi \quad (6)$$

$$E_\Phi = \frac{\sin\left(\frac{KW \sin\theta \sin\Phi}{2}\right)}{\left(\frac{KW \sin\theta \sin\Phi}{2}\right)} \cos\left(\frac{KL}{2} \sin\theta \cos\Phi\right) \cos\theta \sin\Phi \quad (7)$$

Where K is the wave number, W, L represents the width of the rectangular microstrip patch, and the length of the rectangular microstrip patch is the field pattern of an element, which is the magnitude of the electric field components. It is given by

$$F(\theta, \Phi) = \sqrt{E_\theta^2 + E_\Phi^2} \quad (8)$$

The normalized total electric field equation in dB is given as

$$E(u) = 20 \log\left(\frac{E(\theta, \Phi)}{E(\theta, \Phi)_{max}}\right) \text{dB} \quad (9)$$

IV. Results and Discussion

The designed amplitude distribution using the random method is presented in Figure 2, and the corresponding phase distribution using the stationary phase concept is presented in Figure 3.

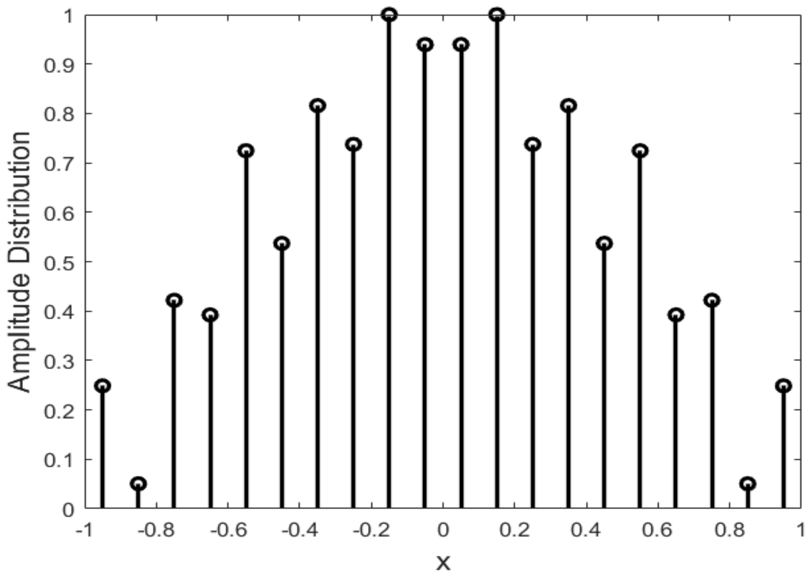

Fig. 2. Random amplitude distribution for N = 20 Elements

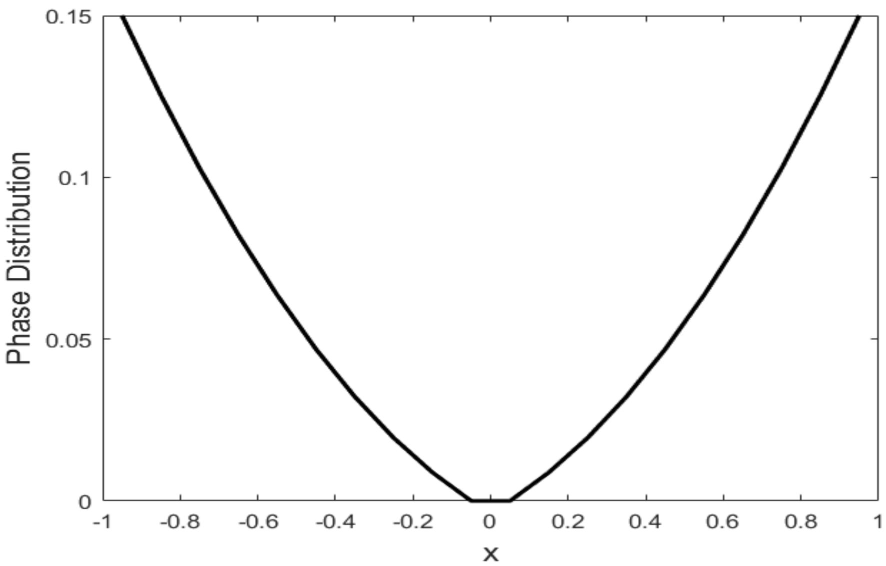

Fig. 3. Phase amplitude distribution for N = 20 Elements

By introducing the above amplitude and phase distributions for the elements of the arrays, the sum and difference are generated, and the desired side lobe level, which is -30dB, is obtained for all the ideal and practical antenna arrays. These radiation patterns in the 'u' domain are presented in Figures 4 to 6.

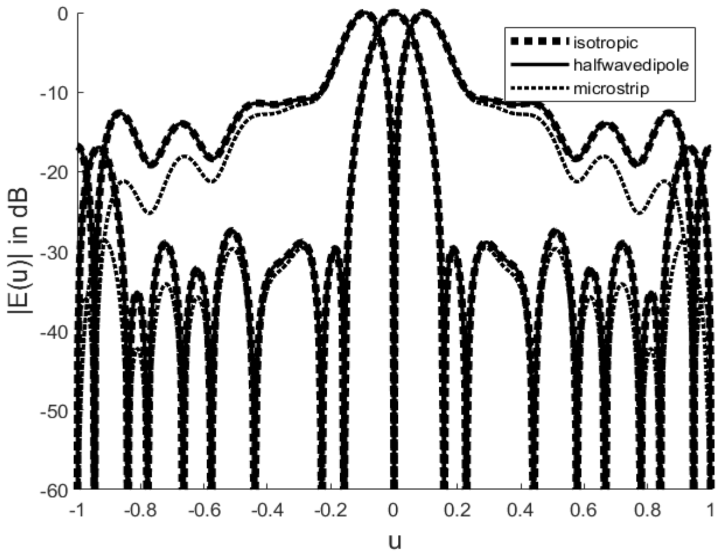

Fig 4. Sum and Difference patterns comparison with amplitude-only control for N = 20 Elements

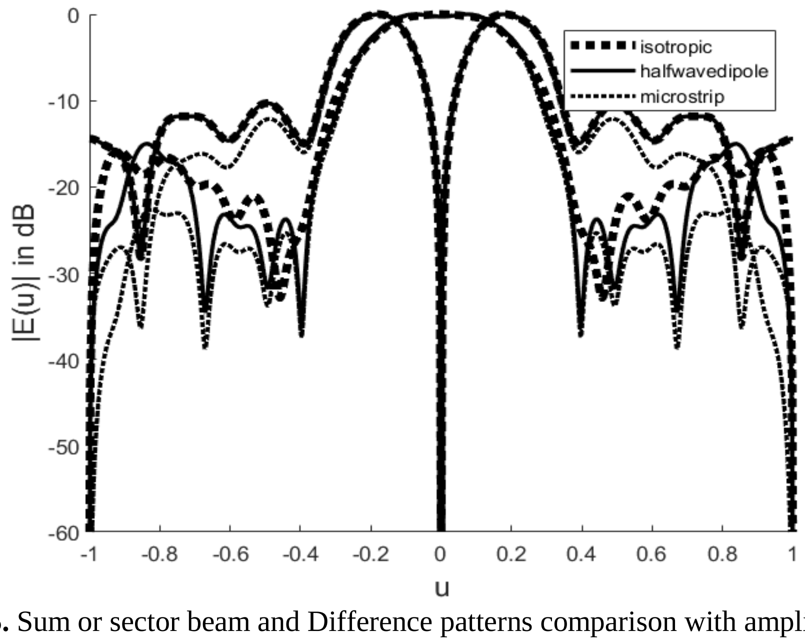

Fig 5. Sum or sector beam and Difference patterns comparison with amplitude and phase control for N = 20 Elements

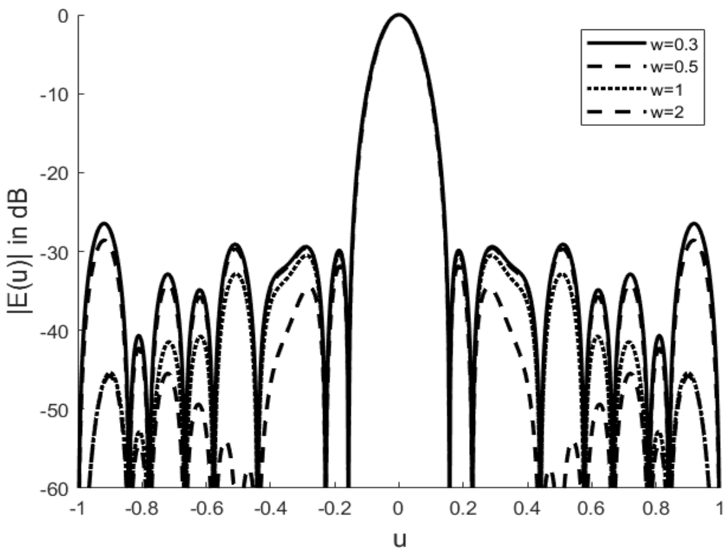

Fig. 6. Sum patterns comparison with amplitude-only control for N = 20 Microstrip Elements with different widths

Figure 4 presents the sum and different patterns with amplitude-only control for the arrays of ideal antenna arrays of isotropic elements and practical antennas such as halfwave dipole and microstrip antennas. Figure 5 represents sector beams over a desired angular region, and difference patterns are generated by introducing amplitude and phase control for both ideal and practical antenna arrays. Figure 6 represents patterns of arrays of microstrips for the different widths of the rectangular patch.

It is evident from the results that the amplitude distribution has the highest value towards the center of the array and has lower values towards the end. On the other hand, the phase distribution Figure 3 shows the lower value at the center and the highest value at the ends. The difference patterns in Figures 4 and 5 have a deep null with an optimized difference slope. In Figure 5, the sector beam is suitably broadened with an appropriate additional phase. From Figure 6, the radiation pattern is influenced by the physical parameters of the microstrip antenna.

V. Conclusion

The designed sum and difference patterns for ideal and practical elements are well controlled in terms of SLL reduction in the sum pattern, deep null in boresight direction in the difference pattern, and sector beam with desired angular width by using the random amplitude distribution and phase distribution using stationary phase concept. The practical elements considered are halfwave dipoles and microstrip patch arrays. The side lobe level is restricted to -30 db. The results of this work are extremely useful for array designers in Défense radar applications. The work can be further extended to restrict the side lobe level to more than -30 dB and on other practical antenna elements.

Conflict of Interest:

All the authors of this manuscript declared that they do not have any kind of financial interests.

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