JOURNAL OF RESEARCH of the National Bureau of Standards—B. Mathematics and Mathematical Physics
Vol. 67B, No. 3, July–September 1963

Zeros of First Derivatives of Bessel Functions of the First Kind, $J'_n(x)$, $21 \leq n \leq 51$, $0 \leq x \leq 100$

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(April 5, 1963)

A table of zeros of first derivatives of Bessel functions of the first kind, $J'_n(x)$, is presented for $21 \leqslant n \leqslant 51$, $0 \leqslant x \leqslant 100$. A brief discussion of table generation and accuracy is included.

1. Introduction

Zeros of

$$J'_n(x)=0, \ (n=0, 1, 2, 3, \ldots) \tag{1}$$

are frequently required for the solution of problems in mathematical physics and engineering. Typical problems of this kind occur in the theory of heat conduction [1],[1] hydrodynamics, finite Hankel transforms, Fourier-Bessel expansions, etc.

In conjunction with a heat transfer problem [2], the authors conducted a literature search in the spring of 1961 to find a table of zeros of $J'_n(x)$. No adequate tables were found at that time, and a table of such zeros for $0 \leqslant n \leqslant 51$, $0 \leqslant x \leqslant 100$ was generated. It was subsequently learned that the new Royal Society Tables [3], published in 1960 and available in 1961, contained zeros of $J'_n(x)$ for orders $0 \leqslant n \leqslant 20$. For this reason the present table is given for orders $21 \leqslant n \leqslant 51$ and $0 \leqslant x \leqslant 100$. A thorough summary of existing tables is given on page 411 of volume I [4].

2. Determination of the Positive Roots of $J'_n(x)$

As is well known, all the roots of $J'_n(x)=0$, $n>-1$, are real (see [5]). The determination of these roots for $0 \leqslant x \leqslant 100$ and $n=21, 22, 23, \ldots, 51$ was carried out on the IBM 1620 computer. The method employed was a modification of Newton's method. If x_k is an approximate root of $F(x)=0$, an improved value, x_{k+1}, is found by Newton's method as

$$x_{k+1}=x_k-\frac{F(x_k)}{F'(x_k)}.$$

The modified form of the method used in the computation of table 1 found x_{k+1} from

$$x_{k+1}=x_k-\frac{J'_n(x_k)}{\alpha},$$

where

$$\alpha=\frac{J'_n(x_0+0.005)-J'_n(x_0-0.005)}{0.01},$$

and x_0 is the first approximation of a root of equation (1). $J'_n(x)$ as used in this formula was found by a truncation of the series

$$J'_n(x)=\sum_{m=0}^{\infty}(-1)^m\frac{(2m+n)\left(\frac{x}{2}\right)^{2m+n-1}}{2(m!)(m+n)!}.$$

The series was truncated to produce $J'_n(x)$ accurate at least to the order of 10^{-15}.

The first approximation, x_0, to a root of $J'_n(x)$ was obtained from the Harvard tables [6]. The iteration discussed above was carried out until the change in the approximate value of a root between successive iterations had become less than 5×10^{-9}, or 10 iterations had been performed, whichever came first.

Machine running time was approximately one minute per root for small s increasing to approximately eight minutes per root for large s. Advantage was taken of the variable word length feature of the IBM 1620 computer, and 50 significant figures were carried in the computer.

The use of asymptotic (McMahon) series to compute the zeros of $J'_n(x)=0$ was also tried. When using the first four terms of the appropriate series, the accuracy obtained was not adequate for present purposes. For instance, when $n=0$, agreement to four decimal places requires that $s \geqslant 3$, but when $n=15$, agreement to four decimal places requires that $s \geqslant 18$. This method of computation was found to be awkward and was subsequently abandoned.

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[1] Figures in brackets indicate the literature references at the end of this paper.

TABLE 1. Zeros $j'_{n,s}$ of $J'_n(x)$

s \ n	21	22	23	24	25	26	27	28
1	23.25482051	24.28938554	25.32292421	26.35550968	27.38720713	28.41807483	29.44816521	30.47752554
2	28.81559026	29.91614781	31.01399843	32.10931996	33.20227214	34.29299903	35.38163108	36.46828685
3	33.11916251	34.26076830	35.39878197	36.53342770	37.66490790	38.79340601	39.91908887	41.04210875
4	37.05164392	38.22489744	39.39397753	40.55913306	41.72058970	42.87855284	44.03320998	45.18473289
5	40.78864004	41.98788278	43.18254757	44.37289611	45.55916665	46.74157681	47.92032600	49.09559743
6	44.40300395	45.62431208	46.84075435	48.05259808	49.26008750	50.46344645	51.66288070	52.85857983
7	47.93297704	49.17342240	50.40879603	51.63936621	52.86537891	54.08706022	55.30461857	56.51824657
8	51.40136592	52.65866144	53.91073936	55.15786592	56.40028590	57.63822500	58.87189183	60.10147963
9	54.82293308	56.09523556	57.36221966	58.62414749	59.88126077	61.13378297	62.38192112	63.62586750
10	58.20780036	59.49358979	60.77399447	62.04927114	63.31965714	64.58537241	65.84662124	67.10359375
11	61.56321210	62.86121252	64.15378858	65.44119072	66.72365106	68.00138519	69.27459380	70.54346404
12	64.89452898	66.20365410	67.50733617	68.80581881	70.09932836	71.38807549	72.67225671	73.95205564
13	68.20582532	69.52513956	70.83900854	72.14766879	73.45134051	74.75022911	76.04452654	77.33441251
14	71.50026659	72.82895627	74.15221157	75.47026176	76.78332077	78.09158850	79.39525213	80.69448717
15	74.78035780	76.11770942	77.44964789	78.77639527	80.09815911	81.41513374	82.72750140	84.03543330
16	78.04811263	79.39349598	80.73349570	82.06832667	83.39819010	84.72327469	86.04375773	87.35980602
17	81.30517182	82.65802681	84.00553424	85.34790193	86.68532484	88.01798612	89.34605807	90.66970305
18	84.55288816	85.91271419	87.26723391	88.61664829	89.96114613	91.30090509	92.63609256	93.9668665
19	87.79238862	89.15873605	90.51982252	91.87584232	93.22697825	94.5734026	95.9152779	97.252758
20	91.02462083	92.39708397	93.76433469	95.12656080	96.4839394	97.83664	99.18481	
21	94.2503882	95.6285994	97.0016496	98.369720	99.73298			
22	97.470377	98.85400						

s \ n	29	30	31	32	33	34	35	36
1	31.50619868	32.53422356	33.56163572	34.58846766	35.61474922	36.64050785	37.66576885	38.69055565
2	37.55307443	38.63609270	39.71743238	40.79717690	41.87540324	42.95218254	44.02758073	45.10165905
3	42.16260504	43.28070570	44.39652854	45.51018228	46.62176750	47.73137747	48.83909883	49.94501228
4	46.33327932	47.47899456	48.62201276	49.76245810	50.90044573	52.03608272	53.16946879	54.30069698
5	50.26755989	51.43636931	52.60217002	53.76509596	54.92527166	56.08281316	57.23782876	58.39041974
6	54.05071903	55.23946052	56.42495487	57.60734209	58.78675269	59.96330850	61.13712347	62.30830435
7	57.72812261	58.93441230	60.13726972	61.33683844	62.53325256	63.72663752	64.91711085	66.10478288
8	61.32716786	62.54912345	63.76750203	64.98244897	66.19410026	67.40258336	68.60801790	69.81051636
9	64.86580101	66.10188848	67.33428573	68.56313857	69.78858366	71.01074932	72.22975619	73.44571783
10	68.35646723	69.60540730	70.85056897	72.09209754	73.33012943	74.56479294	75.79620886	77.02449111
11	71.80817077	73.06887767	74.32573818	75.57889638	76.82848778	78.07463998	79.31747334	80.55710149
12	75.22764416	76.49918344	77.76682482	79.03071064	80.29097497	81.54774425	82.80113789	84.05126881
13	78.62005552	79.90161382	81.17923628	82.45306311	83.72322656	84.98985154	86.25305616	87.51295225
14	81.98945851	83.28032121	84.56722136	85.85029678	87.12967762	88.40548697	89.67784138	90.94685132
15	85.33909047	86.63862466	87.93417897	89.22588862	90.51388147	91.79827859	93.07919474	94.35673887
16	88.67157668	89.97921796	91.28286992	92.58266499	93.87872862	95.17117970	96.46013108	97.7456900
17	91.98907425	93.30431637	94.61556629	95.92295364	97.2266013	98.526626	99.823138	
18	95.2933761	96.6157625	97.9341594	99.248694				
19	98.585988	99.915104						

s \ n	37	38	39	40	41	42	43	44
1	39.71488993	40.73879184	41.76228012	42.78537226	43.80808458	44.83043235	45.85242988	46.87409061
2	46.17447445	47.24608006	48.31652548	49.38585712	50.45411848	51.52135039	52.58759122	53.65287710
3	51.04919307	52.15171154	53.25263353	54.35202077	55.44993122	56.54641941	57.64153668	58.73533146
4	55.42985428	56.55702215	57.68227699	58.80569058	59.92733042	61.04726012	62.16553970	63.28222582
5	59.54068094	60.68870138	61.83456466	62.97834948	64.12012999	65.25997613	66.39795402	67.53412615
6	63.47695133	64.64315855	65.80701462	66.96860305	68.12800265	69.28528788	70.44052920	71.59379334
7	67.28975730	68.47213170	69.65199810	70.82944334	72.00454949	73.17739421	74.34805104	75.51658976
8	71.01018463	72.20712253	73.40142430	74.59317900	75.78247092	76.96937991	78.15398172	79.33634823
9	74.65874137	75.86892789	77.07637299	78.28116712	79.48339598	80.68314089	81.88047903	83.07548378
10	78.24974724	79.47207895	80.69158247	81.90834900	83.12246507	84.33401283	85.54307039	86.74971206
11	81.79363188	83.02716621	84.25780087	85.48562731	86.71073237	87.93319861	89.15310461	90.37052520
12	85.29824389	86.54216443	87.78312656	89.02122157	90.25653626	91.48915323	92.71915116	93.94660509
13	88.76964580	90.02323738	91.27382253	92.52149207	93.76633247	95.00842607	96.24785140	97.48468340
14	92.21262163	93.47525189	94.73483679	95.99146646	97.24522677	98.49619961	99.74446310	
15	95.63101442	96.90211981	98.17014868	99.43519030				
16	99.0279584							

s \ n	45	46	47	48	49	50	51	
1	47.89542716	48.91645142	49.93717458	50.95760723	51.97775935	52.99764039	54.01725930	
2	54.71724208	55.78071831	56.84333616	57.90512436	58.96611015	60.02631933	61.08577641	
3	59.82784946	60.91913392	62.00922575	63.09816371	64.18598460	65.27272333	66.35841310	
4	64.39737208	65.51102923	66.62324535	67.73406610	68.84353482	69.95169273	71.05857906	
5	68.66855175	69.80128692	70.93238495	72.06189644	73.18986951	74.31634998	75.44138148	
6	72.74514357	73.89463994	75.04233952	76.18829659	77.33256282	78.47518745	79.61621745	
7	76.68307658	77.84757445	79.01014324	80.17083993	81.32971886	82.48683185	83.64222836	
8	80.51654782	81.69464548	82.87070314	84.04477980	85.21693177	86.38721278	87.55567420	
9	84.26822496	85.45876907	86.64717947	87.83351663	89.01783829	90.20019962	91.38065337	
10	87.95400864	89.15602759	90.35583329	91.55348723	92.74904815	93.94257225	95.13411332	
11	91.58553174	92.79819229	94.00857188	95.21673264	96.42273401	97.62663288	98.82848375	
12	95.17158660	96.39416407	97.61440284	98.83236544				
13	98.71899365	99.9508506						

3. Tabulation Scheme: Accuracy Evaluation

Table 1 presents the computed roots. All entries were tested for accuracy to the number of places shown by observing the effect of perturbing the last digit of each entry. The digit which resulted in the smallest absolute value of the function was then selected. Thus, the only possibility of error when 50 decimal places are carried, is an accumulated round-off error, a computer malfunction, or a print-out error. Accumulated round-off errors can occur at larger x. Typographical errors have been minimized by several table checks. We note that the number of decimal places decreases for n small and s large. This is due to poor convergence of the successive iterations of the modified Newton's method used.

Where possible, the roots in our entire computation $0 \leq n \leq 51$, $0 \leq X \leq 100$ were compared with those given in [7 and 8]. Fourteen of the larger roots of [7] do not agree with the corresponding results of our computation. The largest discrepancy occurs in the case of the seventh root of $J_3'(x)=0$ which, in [7], is given as 24.1469, whereas the value by our method rounded off to four decimal places, is 24.1449. Six roots of [8] do not agree with our values. The largest discrepancy occurs in the third root $J_2'(x)=0$, which, in [8] is given as 9.965, whereas the value by our computation, rounded off to three decimal places, is 9.969. To test for the chance of error in machine output, the 14 cases with discrepancies in [7] and the 6 cases of [8] were separately re-run by summing the series of $J_n'(x)$ with the values of our computation rounded off to four places and three places respectively, and then summing with the corresponding values of [7 and 8]. In every case the rounded-off values by the method of section 2 gave the better approximation to the root. These discrepancies are also discussed in [4 and 9].

Another check on the present computation was afforded by the application of the Lagrange interpolating polynomial used in conjunction with the Harvard Tables [6]. This method requires obtaining the Lagrange interpolating polynomial for $J_n'(x)$ through k points in the vicinity of the root. For each of the k values of x we obtain the value of $J_n'(x)$ from the formula $2J_n'(x)=J_{n-1}(x)-J_{n+1}(x)$, where $J_{n-1}(x)$ and $J_{n+1}(x)$ are obtained from [6]. The root of the interpolating polynomial was then found by a modification of Newton's method. When this method was used with $k=4$ in a limited number of cases, ($n=1$, $1 \leq s \leq 16$, and $n=15$, $s=1$), the roots so obtained coincided to six decimal places with those obtained by the computation of section 2. The Lagrange interpolation method was originally intended for the computation of table 1, but was abandoned because of the excessive labor required for data input to the computer from the Harvard Tables.

Finally, the values for $0 \leq n \leq 20$ were compared at all common values with the Royal Society Tables [3]. It was found that eight decimals agreed for all n and $x < 78$. For some n and $x > 78$ a last decimal round-off discrepancy is observed. It is concluded that the tables for $21 \leq n \leq 51$ are correct as presented for x smaller than about 80, and may err at the last decimal place shown for other entries.

The authors are grateful to Professor J. R. Britton of the University of Colorado for some of the references and to Messrs. J. E. Butler and P. H. Dorsey of the Martin Company for performing the numerical computation.

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(Paper 67B3–102)

Publications of the National Bureau of Standards*

Selected Abstracts

On the fourth order Hamiltonian of an asymmetric rotor molecule of orthorhombic symmetry, Wm. B. Olson and H. C. Allen, Jr., *J. Research NBS* **67A** *(Phys. & Chem.) No. 4, 357–362 (July–Aug. 1963).*
The fourth order Hamiltonian of an asymmetric rotor molecule of orthorhombic symmetry given recently has been considerably reduced in complexity through the use of equations derived from the basic relationship among the angular momentum operators. The reduced Hamiltonian obtained provides a most convenient starting point for the calculation of rotational energy levels from a solution of the complete secular equation, for a perturbation theory solution to the problem of centrifugal distortion, and for the deduction of sum rules among the energy levels.

Asymptotic behavior of the current on an infinite cylindrical antenna, K. S. Kunz, *J. Research* **67D** *(Radio Prop.) No. 4, 417 (July–Aug. 1963).*
An asymptotic expression is obtained for the current distribution on the outside surface of an infinitely long, perfectly conducting, hollow cylindrical antenna that is fed by an infinitesimally narrow circumferential gap. This asymptotic expression involves two series. The first series is expressed in reciprocal powers of log $(2|z|/j\Gamma^2ka^2)$, where $|z|$ is the distance from the gap, log Γ is Euler's constant, k is the propagation constant, and a is the radius of the antenna. The second series is a similar series multiplied by $1(k|z|)$. The first series is dominant and its first five terms yield values for the magnitude and phase of the current that for even moderately thick antennas (circumferences as large as $\lambda/3$) are accurate to within about one percent in as close as $\lambda/3$ of the gap. This is shown by a comparison of the values of the current obtained from these terms with the numerically computed values of Duncan (1962). Asymptotic expressions for the current found in the literature resemble the first term of this dominant series and are accurate only at relatively large distances from the gap—except for very thin antennas.

A dipole approximation of the backscattering from a conductor in a semi-infinite dissipative medium, M. B. Kraichman, *J. Research NBS* **67D** *(Radio Prop.) No. 4, 433 (July–Aug. 1963).*
The backscattering of a uniform plane wave by a conductor in a semi-infinite dissipative medium is discussed. The conductor is assumed to act as both an electric and a magnetic dipole with moments which are obtained from the electric magnetic polarizabilities of the conductor, respectively. Using these induced moments, expressions are derived for the backscattered electric field at a point on the surface of the dissipative halfspace directly above the dipoles. Both harmonic and transient excitation are considered.

A survey of some mathematical models in the theory of reliability, G. H. Weiss, *Book, Statistical Theory of Reliability, Ed. M. Zelen, pp. 3–54 (Univ. of Wisconsin Press, Madison, Wis., 1963).*
This paper contains a survey of models for systems which are subject to various types of failures. Topics which are discussed are, topological aspects of reliability, time-dependent reliability, and the analysis of maintenance and inspection policies.

Hartree-Fock approximation of CH_4 and NH_4^+, M. Krauss, *J. Chem. Phys.* **38,** *No. 2, 564–565 (Jan. 15, 1963).*
Molecular energies, which approach the Hartree-Fock limit, have been computed for the CH_4 and NH_4^+ molecules at their equilibrium distances. These results verify the suitability of exponential quadratic functions as basis functions in molecular calculations.

Some stochastic processes in polymer systems, J. Mazur, *J. Chem. Phys.* **38,** *No. 1, 193–201 (Jan. 1, 1963).*
Certain distributional problems involving polymer configurations can be treated as special classes of stochastic processes known as regenerative processes. These processes have the property that the interval (of time or of length) between two consecutive events is a random variable. The method of regeneration point is applied to the problem of random crystallization of polymers and to the problem of force-length relationships in a one-dimensional simulation of a polymer network. By assuming that the events of randomly placing crystalline units on a polymer chain are statistically independent, and that the probability of the first event occurring in a given interval is a simple step function, the direct application of the method of regeneration point leads to a well-known equation from the theory of molecular distribution in one-dimensional hard-core fluids. In the second problem it is assumed that a single polymer chain consists of mesh points connected by flexible chains. A restriction is imposed that these mesh points cannot pass through each other. The molecular distribution functions for these mesh points are derived with the help of the regeneration-point process. By applying this method, the relationships of the network extension to the fixed force are derived. It is also found that the affine transformation rule for the force-biased distribution of chain lengths holds strictly only if the array represents a Poisson distribution of mesh points.

On the three-particle scattering operator in classical gases, J. Weinstock, *Physics Letters* **3,** *No. 6, 260–262 (Feb. 1, 1963).*
The three-particle scattering operator is the central quantity which must be calculated in order to determine the density dependence of transport coefficients in gases. A perturbation method is presented, for such a calculation, which is based upon the "binary collision expansion" of the "Greens function" form of the three-particle scattering operator. In addition, it is pointed out that the n-particle scattering operators of non-equilibrium statistical mechanics are actually the asymptotic forms of more general time dependent n-particle operators, and that a complete description of non-equilibrium phenomena may be obtained from a knowledge of the time dependence of these more general operators.

Roger Joseph Boscovich and the combination of observations, C. Eisenhart, *Actes Symp. Intern. R. J. Boskovic 1961, pp. 19–25 (1962).*
An historical note on the contributions of Roger Joseph Boscovich (1711–1787) to the art and science of the Combination of Observations. (The present note is an abridged version of the author's paper "Boscovich and the Combination of Observations" cleared by the Editorial Committee on Nov. 19, 1960, for publication as a chapter in the memorial volume Roger Joseph Boscovich, F. R. S.: Studies of His Life and Work, edited by L. L. Whyte to be published in October 1961 by Allen and Unwin, Ltd., London.

Interactions matrix element in a shell model, U. Fano, F. Prats, and Z. Goldsmith, *Phys. Rev.* **129,** *No. 9, 2643–2652 (Mar. 16, 1963).*
The matrix elements of two-particle interactions between states of many-particle configurations are expressed as products of one-particle reduced matrix elements and of a single recoupling coefficient. Applications are given to the Coulomb interaction l^nl' configurations and to all three-electron configurations.

Indication limit, E. L. R. Corliss, *Proc. Fourth Intern. Congr. Acoustics, Pt. I, Paper N22 (Copenhagen, Denmark, Aug. 21–28, 1962).*
From basic considerations, a volume in signal space has been derived, applicable to any analyzer. It is a product of resolution limits in energy, frequency, and time, and depends functionally only upon the signal-to-noise ratio. The derivation demonstrates the rise of statistical features as $S/N \rightarrow 0$.

Other NBS Publications

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Wavelength calibrations in the far infrared (30 to 1000 microns). K. Narahari Rao, R. V. de Vore, and E. K. Plyler.
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