SLAC-PUB-13469
November 24, 2008

# Landau Damping Revisited*

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**Abstract**

Landau damping, as the term is used in accelerator science, is a physical process in which an ensemble of harmonic oscillators—an accelerator beam, for example—that would otherwise be unstable is stabilized by a spread in the natural frequencies of the oscillators. This is a study of the most basic aspects of that process. It has two main goals: to gain a deeper insight into the mechanism of Landau damping and to find the coherent motion of the ensemble and thus the dependence of the total damping rate on the frequency spread.

*Work supported by Department of Energy contract DE-AC02-76SF00515.

## 1. Introduction

Landau damping, as the term is used in accelerator science, is a physical process in which an ensemble of harmonic oscillators—an accelerator beam, for example—that would otherwise be unstable is stabilized by a spread in the natural frequencies of the oscillators.

In its simplest form, the system consists of an ensemble of harmonic oscillators having a spectrum of natural frequencies and being acted on in common by a force that is a function only of the mean displacement of all the oscillators. The common force is often an unavoidable concomitant of the environment of the oscillators, as in the case of a charged-particle beam in a conductive vacuum chamber, where the electromagnetic field induced by the beam centroid acts on the beam particles.

This investigation has two main goals: to gain a deeper insight into the mechanism of Landau damping and to find the actual coherent motion and the dependence of the total damping rate on the frequency spread rather than merely the boundary between stable and unstable motion.

The equation of motion of an oscillator in the ensemble for $t \geq 0$ is

$$\ddot{x}(t) + (\Omega + u)^2 x(t) = F(t), \tag{1}$$

where $x$ is the displacement, $\Omega$ is a fixed positive reference frequency, and the incremental frequency $u$ varies from one oscillator to another. In effect each oscillator is labeled by its $u$-value, and there are as many of these equations as there are oscillators in the system. F(t) is the feedback force.

To analyze the stability of the coherent motion of the system, we consider all the oscillators, having formerly been at rest, to be impulsively set in coherent motion at $t = 0$, each with

$$x(0) = x_0 \quad \text{and} \quad \dot{x}(0) = x_0', \tag{2}$$

where $x_0$ and $x_0'$ are the same for all oscillators. For system stability we require that the coherent signal eventually die out in time.

For convenience we introduce a fixed reference frequency $\Omega$, and characterize the ensemble's spectrum of natural frequencies by a normalized distribution of incremental frequencies $\rho(u)$, the fraction of oscillators having frequencies between $\Omega+u$ and $\Omega+u+du$ being $\rho(u)du$. See Figure 1. The central frequency of the spectrum will be designated by $u_0$, and the width parameter, a positive number, by $\delta$. It will always be the case that

$$|u| \ll \Omega, \tag{3}$$

and it will often be useful to make approximations based on the smallness of $u$.

We shall frame the description of the motions of the system using complex notation with the convention that the real part of the solution is the physical motion. In this framework, the feedback process can then be formulated in terms of an impedance $Z$,

$$F(t) = Z\,\langle x \rangle, \tag{4}$$

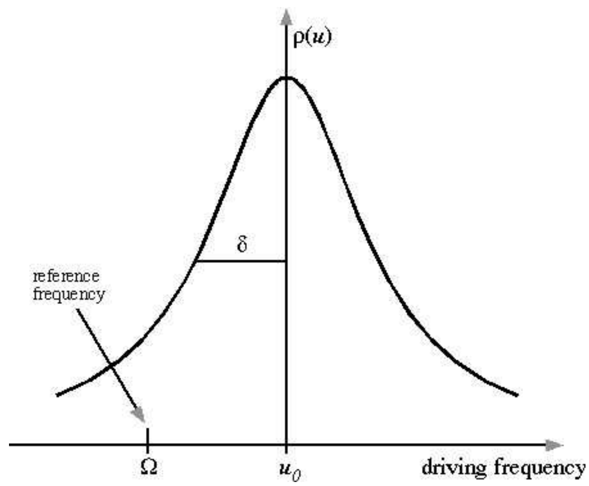


Figure 1: The incremental frequency disrtibution.

where $Z$ is a complex constant and $\langle x \rangle$ is the mean displacement of the oscillators. *N. B.* An impedance is defined for a particular complex sinusoid in time, so the choice between $e^{i\omega t}$ and $e^{-i\omega t}$ is made in defining the impedance. In our case the choice is $e^{-i\omega t}$. See Ref. 5.

**2. Special case: $\delta = 0$; Intrinsic instability**

To begin with we shall consider the behavior of the ensemble with no energy spread and consequently no Landau damping. In this case $u = 0$ for all the oscillators, so they obey the same equation of motion, and so does the mean displacement.

$$\langle \ddot{x} \rangle + \Omega^2 \langle x \rangle = Z \langle x \rangle \tag{5}$$

The function $\langle x \rangle = e^{\gamma t}$ is a solution if

$$\gamma^2 + (\Omega^2 - X) = 0. \tag{6}$$

There are two distinct solutions of (6) but only one of them corresponds to the definition of the impedance given above. For our purposes we can take $Z$ to be purely imaginary and small in comparison with $\Omega^2$.

$$Z = iX, \qquad (X \text{ real and } |X| \ll \Omega^2) \tag{7}$$

With these conditions and choosing the solution corresponding to the impedance, we get

$$\gamma = -\sqrt{-\Omega^2 - iX} \approx -i\Omega - X/2\Omega, \tag{8}$$

so the general solution is

$$\langle x \rangle = A\, e^{-\alpha t} e^{-i\Omega t}, \tag{9}$$

where $A$ is a complex constant and we have defined the constant $\alpha$.

$$\alpha = \frac{X}{2\Omega} = -\frac{iZ}{2\Omega} \tag{10}$$

The motion is *unstable* if $X < 0$.

### 3. The general case, $\delta > 0$

In the general case of $\delta > 0$, the set of equations for the individual oscillators do not collapse into a single equation for $\langle x \rangle$ as in the previous case, and the solution is more complicated. The different oscillators are all driven by the same force term, and they all have the same initial conditions, but they have different natural frequencies. Temporarily enumerating the oscillators by subscripts, we have the equation set,

$$\begin{aligned}
\ddot{x}_1 + (\Omega + u_1)^2 x_1 &= Z\langle x \rangle, \\
\ddot{x}_2 + (\Omega + u_2)^2 x_2 &= Z\langle x \rangle, \\
\ddot{x}_3 + (\Omega + u_3)^2 x_3 &= Z\langle x \rangle, \\
&\vdots
\end{aligned}$$

where the driving term involves the average of the individual displacements $\langle x \rangle$,

$$\langle x \rangle = \frac{1}{N} \sum_{k=1}^{N} x_k.$$

In this formula $N$ is the total number of oscillators. In practice the ensemble is large enough that we can treat $u$ as a continuous variable, and accordingly we convert this sum into an integral,

$$\langle x \rangle = \int_{-\infty}^{\infty} du \rho(u) x_u(t), \tag{11}$$

where $\rho(u)$ is the normalized distribution function referred to in the Introduction, so that the equation of motion of a single oscillator becomes

$$\ddot{x}_u(t) + (\Omega + u)^2 x_u(t) = Z \int_{-\infty}^{\infty} du \rho(u) x_u(t). \tag{12}$$

To solve this set of equations we express the driving force and the oscillator displacements as harmonic oscillations modulated by slowly-varying envelopes, and we seek self-consistent solutions for the modulating functions.

$$x_u(t) = A_u(t) e^{-i(\Omega+u)t}, \tag{13}$$

$$F(t) = f(t) e^{-i\Omega t}, \tag{14}$$

where $A_u(t)$ and $f(t)$ are presumed to be complex functions of time that vary slowly compared to the oscillatory exponential factors, but are otherwise unspecified. The initial conditions on $A_u$ follow from (2).

$$A_u(0) \approx \left( x_0 + i\frac{x_0'}{\Omega} \right), \tag{15}$$

where we have neglected $\dot{A}_u$ in comparison to $\Omega A_u$.

Next we insert the definitions (13) and (14) into to the equation of motion (12) to obtain a differential equation between $A_u$ and $f$.

$$\dot{A}_u = i\frac{f}{2\Omega}e^{iut}, \tag{16}$$

where $\ddot{A}_u$ has been neglected in comparison with $\Omega \dot{A}_u$ and (3) has been invoked. This equation leads to the solution,

$$A_u(t) = \left( x_0 + i\frac{x_0'}{\Omega} \right) + \frac{i}{2\Omega}\int_0^t dt' f(t')e^{iut'} \tag{17}$$

Now according to (11) and (13) the average displacement of the ensemble is

$$\langle x\rangle(t) = e^{-i\Omega t}\int_{-\infty}^{\infty} du\, \rho(u)A_u(t)e^{-iut}, \tag{18}$$

and according to (4) $f(t)e^{-i\Omega t} = Z\langle x\rangle$, so self consistency requires

$$f(t) = Z\int_{-\infty}^{\infty} du\, \rho(u)A_u(t)e^{-iut}. \tag{19}$$

And finally using (17), this imperative can be cast as the defining equation for the envelope function $f(t)$.

$$\boxed{f(t) = Z\left( x_0 + i\frac{x_0'}{\Omega} \right) I(t) + \frac{iZ}{2\Omega}\int_0^t dt' f(t')I(t-t'),} \tag{20}$$

where

$$I(t) = \int_{-\infty}^{\infty} du\, \rho(u)e^{-iut}, \tag{21}$$

the inverse Fourier transform of the distribution function, the distribution function having been specified in the formulation of the original problem. In the process of solving (20) for $f$, the Landau damping rate is revealed, because it is just the rate at which $f$ diminishes with time. Once one has $f$ in hand, $A_u$ can be obtained from (17), and $\langle x\rangle$ can be obtained from from (4) and (14).

## 4. How Landau damping works

Equation (20) holds the key to understanding the Landau damping process. To study its implications, it will be profitable to specialize and simplify it somewhat, while retaining most of its applicability. For this purpose we define the constant,

$$f_0 = Z\left(x_0 + i\frac{x_0'}{\Omega}\right), \tag{22}$$

and we assume the impedance $Z$ to be purely imaginary, the case of greatest interest. The impedance must have an imaginary part in order to have energy transfer between the oscillators and the agency generating the force $F$, and as a result to have damping or antidamping. This also has the consequence that $f_0$ will be $\pi/2$ out of phase with the displacement amplitude $(x_0 + ix_0'/\Omega)$. In these circumstances we can use the constant $\alpha$ defined in (10).

With these definitions (20) takes the compact form

$$f(t) = f_0 I(t) - \alpha\int_0^t dt' f(t')I(t-t'). \tag{23}$$

For interpreting this equation, we note first the important fact that $I(t)$, the inverse Fourier transform of the frequency distribution, is just the decaying coherent signal $\langle x\rangle$ due to the decoherence of the oscillators after an impulsive disturbance of the ensemble. This is easy to see. After the the impulse each oscillator's displacement is

$$x_u(t) = \left(x_0 + i\frac{x_0'}{\Omega}\right)e^{-i(\Omega+u)t}.$$

Therefore, from (11)

$$\langle x\rangle = \left(x_0 + i\frac{x_0'}{\Omega}\right)e^{-i\Omega t}\int_{-\infty}^{\infty} du\rho(u)e^{-iut} = \left(x_0 + i\frac{x_0'}{\Omega}\right)I(t)e^{-i\Omega t}. \tag{24}$$

The envelope of the decay is proportional to $I(t)$.

Returning to (23) first term on the right simply represents the decoherence of the initial signal $f_0$. The second term represents the effect of the force $F$ generated by the coherent displacement. Its integrand is the product of the strength of the signal $f$ at $t'$ and a factor $I(t-t')$ which accounts for the diminution of the signal in the time interval $(t-t')$ due to decoherence. This diminution is the essence of Landau damping. If $\alpha$ is negative, so that the undiminished signal would tend to make the motion grow, the decoherence process competes with the growth process, and if it is fast enough, may overcome the growth and lead to decay. On the other hand, if $\alpha$ is positive, so that the undiminished signal would damp the motion, the decoherence simply increases the damping.

If there is no Landau damping ($\delta = 0$) the distribution becomes a delta function, so that $I(t) = 1$ and $f(t)$ obeys

$$f(t) = f_0 - \alpha \int_0^t dt' f(t'),$$

which is just the integral of the simple equation $\dot{f} + \alpha f = 0$. As discussed in Section 2, the motion is stable or unstable if $\alpha$ is positive or negative respectively. Landau damping is not needed in the intrinsically stable case, although in most particle beam systems it is present nonetheless, and it simply increases the damping rate.

Since Landau damping is the result of competition between exponential growth and decoherence, the outcome of the competition depends on the form of $I(t)$, the Fourier transform of the frequency distribution function. For any distribution, the transform will be a decreasing function of time. Even so, the character of the decrease is important, because the competing growth process is an exponential one, and we cannot expect a less powerfully decaying decoherence to overwhelm such a growth process.

In the following sections we shall apply several methods to the solving of (23), beginning with an exact solution for the case of a Lorentzian spectrum of frequencies.[1]

## 5. An example: Lorentz distribution

An ensemble with natural frequencies distributed according to a Lorentz spectrum offers a particularly congenial application of this formulation, because its inverse Fourier transform is an exponential function. The Lorentz distribution centered at $u = 0$ ($u_0 = 0$) is

$$\rho(u) = \frac{\delta}{\pi(\delta^2 + u^2)}, \tag{25}$$

and

$$I(t) = e^{-\delta t}. \tag{26}$$

From (20) we obtain

$$Z\left(x_0 + i\frac{x_0'}{\Omega}\right) + \frac{iZ}{2\Omega}\int_0^t dt' f(t') e^{\delta t'} = f(t) e^{\delta t}. \tag{27}$$

Taking the derivative with respect to time we obtain the differential equation

$$\dot{f} + \left(\delta - \frac{iZ}{2\Omega}\right) f = 0, \tag{28}$$

[1] Because of the approximation made in (16) an exact solution of (23) leads to a slightly inexact solution for $\langle x\rangle$, but of course the error is small.

to which the general solution is

$$f(t) = f_0 \, \exp\left[-\left(\delta - \frac{iZ}{2\Omega}\right)t\right] = f_0 \, \exp\left[-\left(\delta + \alpha\right)t\right], \tag{29}$$

The function $f(t)$ is the slowly varying envelope of the driving force, and it is related to the coherent amplitude by

$$\langle x\rangle(t) = \frac{f(t)}{Z} e^{-i\Omega t} = \left(x_0 + i\frac{x_0'}{\Omega}\right) \exp\left[-\left(\delta + \alpha\right)t\right] e^{-i\Omega t}. \tag{30}$$

If we let $\delta$ go to zero, which is equivalent to setting all the natural frequencies to $\Omega$, we have

$$\langle x\rangle(t) = \left(x_0 + i\frac{x_0'}{\Omega}\right) \exp\left(-i\Omega - \alpha\right)t, \tag{31}$$

in accordance with (8) in Section 2. The envelope of the displacement of a single oscillator is given in terms of $f(t)$ by (17).

$$A_u(t) = \left(x_0 + i\frac{x_0'}{\Omega}\right) \left[\frac{iu - \delta - \alpha \exp[iut - \delta\, t - \alpha t]}{iu - \delta - \alpha}\right]. \tag{32}$$

Defining the *total damping rate* $\alpha_T$,

$$\alpha_T = \alpha + \delta. \tag{33}$$

The total damping rate increases linearly with the frequency spread. In most cases of interest, $\alpha$, the intrinsic rate, is negative, which leads us to the conclusion that the frequency spread introduced to produce Landau damping must be comparable to the instability growth rate in order to be effective.

In the case of the Lorentz spectrum, we can define the Landau damping rate, as distinct from the intrinsic damping rate $\alpha$, as simply being equal to $\delta$.

## 6. Gaussian distribution—late-term decay

In the foregoing section the solution went quite smoothly, mainly because the inverse Fourier transform (26), which appears in the first term on the right side of (20), is an exponential function and admits an exponential solution for the envelope function. Indeed (20) cannot be satisfied by an exponential solution for $f$ in the case of any other frequency distribution.

Even so, we may be able to find useful approximations for other spectra, because our main interest is in the long-term stability of the coherent motion. If we can determine conditions under which the asymptotic motion is a decaying exponential, we shall have achieved the bulk of our goal. For an example of this approach we consider the Gaussian frequency distribution.

$$\rho(u) = \frac{e^{-u^2/2\delta^2}}{\sqrt{2\pi}\delta} \tag{34}$$

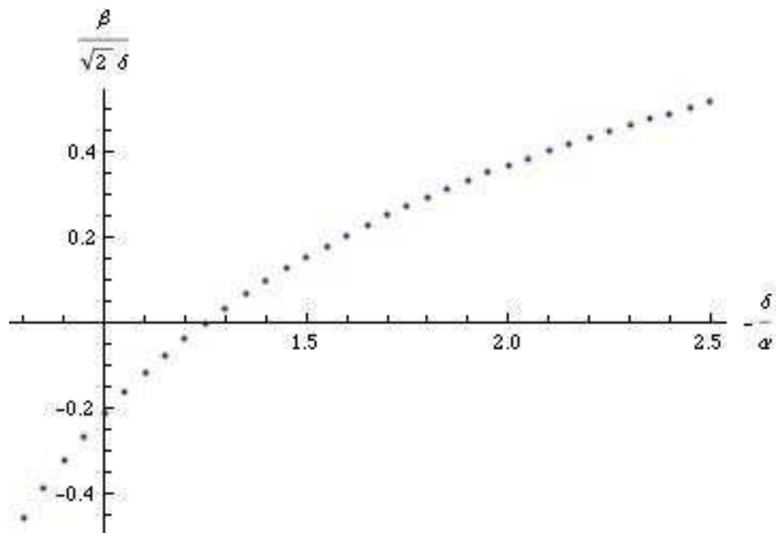


Figure 2: Numerical solutions of (39) showing $\beta$ in units of $\sqrt{2}\,\delta$ is plotted against $\delta$ in units of $-\alpha$ for the Gaussian spectrum.

Its inverse Fourier transform is

$$I(t) = e^{-\delta^2 t^2/2}. \tag{35}$$

Substituting this in (23)—which is the same equation as (20)—we get

$$f(t) = f_0 e^{-\delta^2 t^2/2} - \alpha \int_0^t dt' f(t') e^{-\delta^2 (t-t')^2/2}. \tag{36}$$

Now we want to confine our interest to the asymptotic solution when $t \to \infty$. The first term on the right side vanishes, and assuming an exponential solution $f(t \gg 1/\delta) = e^{-\beta t}$, we have

$$\lim_{t\to\infty} e^{-\beta t} = \lim_{t\to\infty} -\alpha \int_0^t dt' e^{-\beta t'} e^{-\delta^2 (t-t')^2/2} \tag{37}$$

$$= -\alpha\ e^{\beta^2/(2\delta^2)} \sqrt{\frac{\pi}{2}} \left[\mathrm{erf}\left(\frac{\beta}{\sqrt{2}\ \delta}\right) + 1\right] e^{-\beta t}, \tag{38}$$

which reveals that the late term behavior of $f(t)$—and therefore of $\langle x \rangle$—in the case of a Gaussian spectrum is indeed exponential, and for stability it is only necessary that $\beta$ be greater than zero in the asymptotic region, where the relation between the decay rate $\beta$ and the frequency spread $\delta$ is

$$1 = \left(\frac{-\alpha}{\delta}\right)\ e^{\beta^2/(2\delta^2)} \sqrt{\frac{\pi}{2}} \left[\mathrm{erf}\left(\frac{\beta}{\sqrt{2}\ \delta}\right) + 1\right]. \tag{39}$$

The solution to this transcendental equation in which $\beta$ in units of $\sqrt{2}\,\delta$ is plotted against $\delta$ in units of $-\alpha$ is shown in Figure 2. The late-term value of $\delta$ required to stabilize the system in this case is about $1.25|\alpha|$,

## 7. A simple order-of-magnitude approximation

In the two preceding examples we found that the frequency spread $\delta$ needed to stabilize an intrinsically unstable ensemble with a growth rate of $-\alpha$ was approximately equal to $|\alpha|$, and we may reasonably speculate that this fact may be a general feature of Landau damping. By making a simple mathematical model of the function $I(t)$ we can see that this is so. The general features of the inverse Fourier transforms of normalized spectra are that $I(0) = 1$ and that they fall toward zero in a time of the order of $1/\delta$. Let us construct a simplified function meeting these criteria.

$$I(t > 0) = \begin{cases} 1 & \text{if } t \leq 1/\delta, \\ 0 & \text{otherwise.} \end{cases} \tag{40}$$

We refer to this as a mathematical model, because while is mimics the characteristics of the inverse Fourier transforms well, it is unphysical because it has a wide spectrum. We seek an asymptotic solution. For the mathematical model and for $t > 1/\delta$ (23) becomes

$$f(t) = -\alpha \int_{t-1/\delta}^{t} dt' f(t'). \tag{41}$$

Let us approximate $f(t')$ by a truncated Taylor series

$$f(t') = f_t + f_t'(t' - t), \tag{42}$$

where $f_t = f(t)$ and $f_t'$ is the derivative of $f$ evaluated at $t$. Equation (41) takes the form

$$f_t = -\alpha \left( \frac{f_t}{\delta} - \frac{f_t'}{2\delta^2} \right), \tag{43}$$

which leads to the following expression for the logarithmic derivative.

$$\beta = -\frac{2\delta(\alpha + \delta)}{\alpha}. \tag{44}$$

Remembering that the intrinsically unstable case has negative $\alpha$'s, it is useful to express the equation thus:

$$\beta = \frac{2\delta(\delta - |\alpha|)}{|\alpha|}. \tag{45}$$

This suggests that *for any narrow bell-shaped frequency distribution, the frequency spread $\delta$ must be greater than the intrinsic growth rate $-\alpha$ for Landau damping to stabilize the system.*

## 8. A numerical solution

Another approach solving (23) is by numerical approximation. The method is straightforward and, with the help of computer programs for symbolic mathematical manipulation (*Mathematica, Maple*), it is quick. A simple implementation is sketched in the following pages. We begin with (23)

$$f(t) = f_0 I(t) - \alpha \int_0^t dt' f(t') I(t - t'),$$

and approximate the integral by a simple rectangular formula.

$$\int_0^t dt' f(t') I(t - t') \approx \Delta t \sum_{j=1}^{k} I(t_k - t_j) f(t_j). \tag{46}$$

With this replacement we obtain

$$f(t_k) = f_0 I(t_k) - \alpha \Delta t \sum_{j=1}^{k} I(t_k - t_j) f(t_j), \qquad k = 1, 2, \ldots, n. \tag{47}$$

We are interested in values of $t$ starting from zero and rising to some $t_{\max}$ equal to a few times $1/\alpha$. For purposes of numerical approximation we choose a set of $n$ evenly spaced values values of $t$, each centered on one of $n$ equal intervals spanning from zero to $t_{\max}$.

$$t_k = \Delta t(k - 1/2), \qquad k = 1, 2, \ldots, n, \tag{48}$$

with

$$\Delta t = t_{\max}/n. \tag{49}$$

The sequence is

$$\{t_k\} = \{\Delta t/2,\ 3\Delta t/2, \ldots\ , (t_{\max} - 1/2)\}. \tag{50}$$

In order to cast the problem in compact matrix notation, we define column-matrices $\mathbf{f}$ and $\mathbf{g}$ with elements

$$f_k = f(t_k) \qquad \text{and} \qquad g_k = f_0 I(t_k), \tag{51}$$

and the triangular matrix $\mathbf{K}$ with elements

$$K_{kj} = \begin{cases} I(t_k - t_j) & \text{if } j \le k, \\ 0 & \text{if } j > k, \end{cases} \tag{52}$$

where $k = 1, 2, \ldots, n$, in terms of which we can write (47) as follows.

$$f_k = g_k - \alpha \Delta t \sum_{j=1}^{n} K_{kj} f_j, \qquad k = 1, 2, \ldots, n, \tag{53}$$

or in matrix notation

$$\mathbf{f} = \mathbf{g} - \alpha\Delta t\,\mathsf{K}\mathbf{f}.$$

This matrix equation is the equivalent of the $n$ equations represented by (47). If we find the solution $\mathbf{f}$, its elements will give us $n$ evenly spaced values of the function $f(t)$. It can be put in the form

$$(\mathsf{I} + \alpha\Delta t\mathsf{K})\mathbf{f} = \mathbf{g} \tag{54}$$

where $\mathsf{I}$ is the identity matrix, and the solution is

$$\mathbf{f} = (\mathsf{I} + \alpha\Delta t\mathsf{K})^{-1}\mathbf{g}. \tag{55}$$

Fortuitously the matrix $(\mathsf{I} + \alpha\Delta t\mathsf{K})$ has left triangular form, so it is well suited to inversion. Note that in consequence of (22) and (10), $\mathbf{g}$ must be imaginary if $\mathbf{f}$ is to be real.

For the *Lorentz distribution* taking $f_0 = 1$

$$g(t) = if_0\,e^{-\delta t}, \tag{56}$$

$$K(t) = e^{-\delta t}, \tag{57}$$

so

$$g_k = f_0\,e^{-\delta t_k}, \tag{58}$$

$$K_{kj} = \begin{cases} e^{-\delta(t_k - t_j)} & \text{if } j \leq k, \\ 0 & \text{otherwise.} \end{cases} \tag{59}$$

It is easy and quick to carry out a solution with $n = 100$ by this method, and the result gives reasonably accurate agreement with the exact result for the Lorentz spectrum, although of course it is an approximation. Moreover it works well for any reasonable spectrum. We have tested this method and produced results—graphs of $f(t)$ *vs.* $t$—for three spectra: the Lorentz, the Gaussian and the rectangular distributions.

## 8. A little history

In the year 1946 Lev Landau, author of the world-famous series of Russian texts on theoretical physics, reported on a process by which potential instabilities in plasma oscillations would be damped by the oscillating electrons themselves.[2]

The process quite naturally came to be called Landau damping, and in 1959 at the MURA accelerator laboratory in the United States, C. E. Nielsen, A. M. Sessler and K. R. Symon introduced it to accelerator theory by applying a similar formulation to longitudinal oscillations of intense beams in circular accelerators.[3]

[2] L.D.Landau, J. Phys. USSR **10**, 25 (1946).

[3] C. E. Nielsen, A. M. Sessler and K. R. Symon, *Proceedings of the Int. Conf. on High-Energy Accelerators and Instrumentation - CERN 1959*, 239 (1959).

The use of an ensemble of simple harmonic oscillators as an exemplar of systems that are subject to Landau damping was introduced by Hugh Hereward of CERN in 1965,[4] in "The Elementary Theory of Landau Damping," a report whose primary purpose was tutorial. This approach was also used by one of us (AC) in his book on collective instabilities.[5] In this report we have followed that example but pursued a different path to our conclusions. We have been aided by conversations with Albert Hofmann, Andrew Sessler and Claudio Pellegrini.

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[4] H. G. Hereward, CERN Report 65-20 (1965).

[5] A. W. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerators*, Wiley, New York, (1993).