

Spectral densities related to some fractional stochastic differential equations

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Abstract

In this paper we consider fractional higher-order stochastic differential equations of the form

$$\left(\mu + c_\alpha \frac{d^\alpha}{dt^\alpha}\right)^\beta X(t) = \mathcal{E}(t), \quad \mu > 0, \beta > 0, \alpha \in (0, 1) \cup \mathbb{N}$$

where $\mathcal{E}(t)$ is a Gaussian white noise. We obtain explicitly the covariance functions and the spectral densities of the stochastic processes satisfying the above equations.

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1 Introduction

In this paper we consider fractional stochastic ordinary differential equations of different form where the stochastic component is represented by a Gaussian white noise. Some of the fractional equations considered here are related to the higher-order heat equations and thus are connected with pseudo-processes.

The first part of the paper considers the following stochastic differential equation

$$\left(\mu + \frac{d^\alpha}{dt^\alpha}\right)^\beta X(t) = \mathcal{E}(t), \quad \beta > 0, 0 < \alpha < 1, \mu > 0, t > 0 \quad (1.1)$$

where $\frac{d^\alpha}{dt^\alpha}$ represents the Weyl fractional derivative. We obtain a representation of the solution to (1.1) in the form

$$X(t) = \frac{1}{\Gamma(\beta)} \int_0^\infty \mathcal{E}(t-z) \int_0^\infty s^{\beta-1} e^{-s\mu} h_\alpha(z, s) ds dz \quad (1.2)$$

where $h_\alpha(z, s)$, $z, s \geq 0$, is the density function of a positively-skewed stable process $H_\alpha(s)$, $s \geq 0$ of order $\alpha \in (0, 1)$, that is with Laplace transform

$$\int_0^\infty e^{-\xi z} h_\alpha(z, s) dz = e^{-s\xi^\alpha}, \quad \xi \geq 0.$$

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For (1.2), we obtain the spectral density

$$f(\tau) = \frac{\sigma^2}{(\mu^2 + 2|\tau|^\alpha \mu \cos \frac{\pi\alpha}{2} + |\tau|^{2\alpha})^\beta}, \quad \tau \in \mathbb{R} \quad (1.3)$$

and the related covariance function.

The second type of stochastic differential equations we consider has the form

$$\left(\mu + (-1)^n \frac{d^{2n}}{dt^{2n}} \right)^\beta X(t) = \mathcal{E}(t), \quad \beta > 0, \mu > 0, n \geq 1, t \in \mathbb{R} \quad (1.4)$$

where $\mathcal{E}(t)$ is a Gaussian white noise. The representation of the solution to (1.4) is

$$X(t) = \frac{1}{\Gamma(\beta)} \int_{-\infty}^{+\infty} \mathcal{E}(t+x) \int_0^\infty w^{\beta-1} e^{-\mu w} u_{2n}(x, w) dw dx \quad (1.5)$$

where $u_{2n}(x, w)$, $x \in \mathbb{R}$, $w \geq 0$ is the fundamental solution to $2n$ -th order heat equation

$$\frac{\partial u}{\partial w}(x, w) = (-1)^{n+1} \frac{\partial^{2n} u}{\partial x^{2n}}(x, w) \quad (1.6)$$

The covariance function of the process (1.5) can be written as

$$\mathbb{E}X(t)X(t+h) = \frac{\sigma^2}{\Gamma(2\beta)} \int_0^\infty dw w^{2\beta-1} e^{-\mu w} u_{2n}(h, w) = \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E}u_{2n}(h, W_{2\beta}) \quad (1.7)$$

where $W_{2\beta}$ is a gamma r.v. with parameters μ and 2β . The spectral density $f(\tau)$ associated with (1.7) has the fine form

$$f(\tau) = \frac{\sigma^2}{(\mu + \tau^{2n})^{2\beta}}, \quad \tau \in \mathbb{R}. \quad (1.8)$$

For $n = 1$, (1.6) is the classical heat equation, $u_2(x, w) = \frac{e^{-\frac{x^2}{4w}}}{\sqrt{4\pi w}}$ and, from (1.7) we obtain an explicit form of the covariance function in terms of the modified Bessel functions. In connection with the equations of the form (1.6) the so-called pseudo-processes, first introduced at the beginning of the Sixties ([7]), have been constructed. The solutions to (1.6) are sign-varying and their structure has been explored by means of the steepest descent method ([11, 1]) and their representation has been recently given in [14].

For the fractional odd-order stochastic differential equation

$$\left(\mu + \kappa \frac{d^{2n+1}}{dt^{2n+1}} \right)^\beta X(t) = \mathcal{E}(t), \quad n = 1, 2, \dots, \quad \kappa = \pm 1, t \in \mathbb{R} \quad (1.9)$$

the solution has the structure

$$X(t) = \frac{1}{\Gamma(\beta)} \int_{-\infty}^{+\infty} \mathcal{E}(t+x) \int_0^\infty dw w^{\beta-1} e^{-\mu w} u_{2n+1}(x, w) dw dx \quad (1.10)$$

where $u_{2n+1}(x, w)$, $x \in \mathbb{R}$, $w \geq 0$ is the fundamental solution to

$$\frac{\partial u}{\partial w}(x, w) = \kappa \frac{\partial^{2n+1} u}{\partial x^{2n+1}}(x, w), \quad \kappa = \pm 1. \quad (1.11)$$

The solutions u_{2n+1} and u_{2n} are substantially different in their behaviour and structure as shown in [14] and [8].

A special attention has been devoted to the case $n = 1$ (and $\kappa = -1$) for which (1.10) takes the interesting form

$$X_3(t) = \frac{1}{\Gamma(\beta)} \int_{-\infty}^{+\infty} \mathcal{E}(t+x) \int_0^\infty w^{\beta-1} e^{-\mu w} \frac{1}{\sqrt[3]{3w}} Ai\left(\frac{x}{\sqrt[3]{3w}}\right) dw dx \quad (1.12)$$

where $Ai(\cdot)$ is the first-type Airy function. The process X_3 can also be represented as

$$X_3(t) = \frac{1}{\mu^\beta} \mathbf{E} \mathcal{E}(t + Y_3(W_\beta)) \quad (1.13)$$

where the mean \mathbf{E} is defined in formula (1.19) below, Y_3 is the pseudo-process related to equation

$$\frac{\partial u}{\partial t} = -\frac{\partial^3 u}{\partial x^3} \quad (1.14)$$

and W_β is a Gamma-distributed r.v. independent from Y_3 and possessing parameters β, μ . Therefore, the covariance function of X_3 has the following form

$$\mathbf{E} X_3(t) X_3(t+h) = \frac{\sigma^2}{\mu^{2\beta}} \mathbf{E} \left[\frac{1}{\sqrt[3]{3W_{2\beta}}} Ai\left(\frac{h}{\sqrt[3]{3W_{2\beta}}}\right) \right] \quad (1.15)$$

where $W_{2\beta}$ is the sum of two independent r.v.'s W_β .

For the solution to the general odd-order stochastic equation we obtain the covariance function

$$\mathbf{E} X(t) X(t+h) = \frac{\sigma^2}{\mu^{2\beta}} \mathbf{E} [u_{2n+1}(h, W_{2\beta})] \quad (1.16)$$

Of course, the Fourier transform of (1.16) becomes, for $\kappa = \pm 1$,

$$f(\tau) = \frac{\sigma^2}{\mu^{2\beta}} \int_{\mathbb{R}} e^{i\tau h} \mathbf{E} [u_{2n+1}(h, W_{2\beta})] dh = \frac{\sigma^2}{(\mu + i\kappa\tau^{2n+1})^{2\beta}}. \quad (1.17)$$

Stochastic fractional differential equations similar to those treated here have been analysed in [2], [4] and [6]. In our paper we consider equations where different operators are involved. Such operators are defined as fractional powers ($\beta > 0$) of operators of order α , for $\alpha \in (0, 1) \cup \mathbb{N}$. The equations we deal with and involving the white noise $\mathcal{E}(t)$ can be interpreted as integral equations. We define as usual (see [18, pag. 110])

$$X(f) = \int \mathcal{E}(s) f(s) ds$$

so that, for each $f, g \in L^2(dx)$, we have that

$$\mathbf{E} X(f) X(g) = \sigma^2 \int f(x) g(x) dx. \quad (1.18)$$

Thus, by considering integral equations, we do not care about assumptions such as sample continuity and differentiability. Moreover, for the sake of clarity we introduce the following conditional expectation

$$\mathbf{E}[\mathcal{E}(t + Y(W))] = \int \mathcal{E}(t + y) \mathbf{P}(Y(W) \in dy) \quad (1.19)$$

where the expectation is performed w.r.t. the probability measure of $Y(W)$. Throughout the paper we consider Y given by:

- the stable subordinator of order $\alpha \in (0, 1]$, denoted by H_α ;

- the pseudo-processes of order $2n$ and $2n + 1$ with $n \in \mathbb{N}$, denoted by Y_{2n} and Y_{2n+1} .

We also denote by W the Gamma r.v. W_β with parameters μ and β such that $W_1 + W_2 \stackrel{d}{=} W_{2\beta}$.

Pseudo-processes have been developed in a series of papers dating back to the Sixties ([3, 9], [7] for the even-order case, [12] for pseudo-processes related to equations with two space derivatives) and recently by Orsingher [13] for the third-order case, Lachal [8] for the general case and also Smorodina and Faddeev [17].

2 Fractional powers of fractional operators

In this section we consider the following generalization of the Gay and Heyde equation (see [4])

$$\left(\mu + \frac{d^\alpha}{dt^\alpha}\right)^\beta X(t) = \mathcal{E}(t), \quad \beta > 0, 0 < \alpha < 1, \mu > 0, t > 0 \quad (2.1)$$

where $\mathcal{E}(t)$, $t \in \mathbb{R}$, is a Gaussian white noise for which (1.18) holds true. Then, we have that $\mathbb{E}\mathcal{E}(t)\mathcal{E}(s) = \sigma^2\delta(t-s)$ where δ is the Dirac function. The fractional derivative appearing in (2.1) must be meant, for $0 < \alpha < 1$, as

$$\frac{d^\alpha}{dt^\alpha}f(t) = \frac{1}{\Gamma(1-\alpha)} \frac{d}{dt} \int_{-\infty}^t \frac{f(s)}{(t-s)^\alpha} ds = \frac{\alpha}{\Gamma(1-\alpha)} \int_0^\infty \frac{f(t) - f(t-w)}{w^{\alpha+1}} dw.$$

For $\alpha = 1$ we have that

$$\frac{d^\alpha}{dt^\alpha}f(t) = \frac{d}{dt}f(t)$$

as usual. Consult, for example, [16, pag. 111] for information on fractional derivatives of this form, called also Marchaud derivatives. For $\lambda \geq 0$, we introduce the Laplace transform

$$\mathcal{L}\left[\frac{d^\alpha f}{dt^\alpha}\right](\lambda) = \int_0^\infty e^{-\lambda t} \frac{d^\alpha}{dt^\alpha}f(t) dt = \lambda^\alpha \mathcal{L}[f](\lambda) \quad (2.2)$$

which can be immediately obtained by considering that

$$\mathcal{L}\left[\frac{d^\alpha f}{dt^\alpha}\right](\lambda) = \frac{\alpha}{\Gamma(1-\alpha)} \int_0^\infty (\mathcal{L}[f](\lambda) - e^{-w\lambda} \mathcal{L}[f](\lambda)) \frac{dw}{w^{\alpha+1}} \quad (2.3)$$

where we used the fact that

$$x^\alpha = \frac{\alpha}{\Gamma(1-\alpha)} \int_0^\infty (1 - e^{-wx}) \frac{dw}{w^{\alpha+1}}, \quad \alpha \in (0, 1), x \geq 0.$$

Lemma 2.1. *The following relationship holds in a generalized m.s. sense*

$$e^{z \frac{d}{dt}} \mathcal{E}(t) = \mathcal{E}(t+z). \quad (2.4)$$

Proof. In view of the Taylor expansion

$$f(x) = \sum_{k=0}^{\infty} f^{(k)}(x_0) \frac{(x-x_0)^k}{k!} \quad (2.5)$$

with $x_0 = t$ and $x = t+z$ we can write

$$e^{z \frac{d}{dt}} f(t) = \sum_{k=0}^{\infty} \frac{z^k}{k!} \frac{d^k}{dt^k} f(t) = f(t+z) \quad (2.6)$$

which holds for a bounded and continuous function $f : [0, \infty) \mapsto [0, \infty)$. Since we can find an orthonormal set, say $\{\phi_j\}_{j \in \mathbb{N}}$, for which (2.6) holds true $\forall j$ and a sequence of r.v.'s $\{a_j\}_{j \in \mathbb{N}}$ such that

$$\lim_{N \rightarrow \infty} \mathbb{E} \left\| \mathcal{E} - \sum_{j=1}^N a_j \phi_j \right\|_2 = 0, \quad (2.7)$$

we can write (2.4). Since \mathcal{E} is a generalized white noise with second moment as in (1.18) we get the claim. \square

Theorem 2.2. *Let us consider the equation (2.1), then a generalized m.s. solution is*

$$\begin{aligned} X(t) &= \frac{1}{\mu^\beta} \mathbb{E}[\mathcal{E}(t - H_\alpha(W_\beta))], \quad \beta > 0, \quad 0 < \alpha < 1, \quad \mu > 0 \\ &= \frac{1}{\Gamma(\beta)} \int_0^\infty dz \int_0^\infty ds s^{\beta-1} e^{-s\mu} h_\alpha(z, s) \mathcal{E}(t - z) \end{aligned} \quad (2.8)$$

Proof. The solution to the equation (2.1) can be obtained as follows

$$\begin{aligned} X(t) &= \left(\frac{d^\alpha}{dt^\alpha} + \mu \right)^{-\beta} \mathcal{E}(t) \\ &= \frac{1}{\Gamma(\beta)} \int_0^\infty s^{\beta-1} e^{-s\mu - s \frac{d^\alpha}{dt^\alpha}} \mathcal{E}(t) ds \\ &= \frac{1}{\Gamma(\beta)} \int_0^\infty s^{\beta-1} e^{-s\mu} \left\{ e^{-s \frac{d^\alpha}{dt^\alpha}} \mathcal{E}(t) \right\} ds. \end{aligned} \quad (2.9)$$

The first step in (2.9) can be justified on the basis of the arguments in Renardy and Rogers [15, pag. 417]) where the representation of fractional power operators is dealt with.

Now, for the stable subordinator $H_\alpha(t)$, $t > 0$, we have that

$$\begin{aligned} e^{-s \frac{d^\alpha}{dt^\alpha}} \mathcal{E}(t) &= \mathbb{E} e^{-H_\alpha(s) \frac{d}{dt}} \mathcal{E}(t) \\ &= \int_0^\infty dz h_\alpha(z, s) e^{-z \frac{d}{dt}} \mathcal{E}(t) \\ &= \int_0^\infty dz h_\alpha(z, s) \mathcal{E}(t - z) \end{aligned} \quad (2.10)$$

where $h_\alpha(z, s)$ is the probability law of $H_\alpha(s)$, $s > 0$. In the last step of (2.10) we used the translation property (2.4). Therefore,

$$X(t) = \frac{1}{\Gamma(\beta)} \int_0^\infty \mathcal{E}(t - z) \int_0^\infty s^{\beta-1} e^{-s\mu} h_\alpha(z, s) ds dz \quad (2.11)$$

is the representation of the solution to the fractional equation (2.1). \square

Remark 2.3. With (2.7) and (1.18) in mind, notice that a representation of (2.8) is given by

$$X(t) = \frac{1}{\mu^\beta} \sum_{j \in \mathbb{N}} a_j \mathbb{E}[\phi_j(t - H_\alpha(W_\beta))], \quad t > 0. \quad (2.12)$$

Remark 2.4. For the case $\alpha \uparrow 1$, $h_\alpha(z, s) \rightarrow \delta(z - s)$ where δ is the Dirac delta function and from (2.4) we infer that

$$X(t) = \frac{1}{\Gamma(\beta)} \int_0^\infty e^{-\mu s} s^{\beta-1} \mathcal{E}(t - s) ds \quad (2.13)$$

is a generalized solution to

$$\left(\mu + \frac{d}{dt}\right)^\beta X(t) = \mathcal{E}(t). \quad (2.14)$$

Consult on this point [6]. A direct proof is also possible because from (2.9) we have that

$$\begin{aligned} X(t) &= \frac{1}{\Gamma(\beta)} \int_0^\infty s^{\beta-1} e^{-\mu s} e^{-s \frac{d}{dt}} \mathcal{E}(t) ds \\ &= \frac{1}{\Gamma(\beta)} \int_0^\infty s^{\beta-1} e^{-\mu s} \mathcal{E}(t-s) ds. \end{aligned} \quad (2.15)$$

In the last step we applied (2.4).

Remark 2.5. For $\alpha = 1$ and $\beta = 1$, we observe that (2.1) coincides with the Langevin equation and (2.15) can be reduced to the following form of the Ornstein-Uhlenbeck process

$$X(t) = \int_{-\infty}^t e^{-\mu(t-s)} \mathcal{E}(s) ds$$

with covariance function

$$\mathbb{E}[X(t+h)X(t)] = \frac{\sigma^2}{2\mu} e^{-\mu|h|}.$$

Our next step is the evaluation of the Fourier transform of the covariance function of the solution to the differential equation (2.1). Let

$$f(\tau) = \int_{-\infty}^{+\infty} e^{i\tau h} \text{Cov}_X(h) dh$$

where

$$\text{Cov}_X(h) = \mathbb{E}[X(t+h)X(t)]$$

with $\mathbb{E}X(t) = 0$.

Theorem 2.6. The spectral density of (2.8) is

$$f(\tau) = \frac{\sigma^2}{(\mu^2 + 2|\tau|^\alpha \mu \cos \frac{\pi\alpha}{2} + |\tau|^{2\alpha})^\beta}, \quad \tau \in \mathbb{R}, \quad 0 < \alpha < 1, \quad \beta > 0. \quad (2.16)$$

Proof. The Fourier transform of the covariance function of (2.8) is given by

$$\begin{aligned} &\int_0^\infty e^{i\tau h} \mathbb{E}X(t)X(t+h) dh \\ &= \frac{1}{\Gamma^2(\beta)} \int_0^\infty e^{i\tau h} dh \int_0^\infty dz_1 \int_0^\infty ds_1 \int_0^\infty ds_2 \int_0^\infty dz_2 s_1^{\beta-1} s_2^{\beta-1} \\ &\quad \times e^{-(s_1+s_2)\mu} h_\alpha(z_1, s_1) h_\alpha(z_2, s_2) \mathbb{E}\mathcal{E}(t-z_1)\mathcal{E}(t+h-z_2) \end{aligned}$$

where

$$\mathbb{E}\mathcal{E}(t-z_1)\mathcal{E}(t+h-z_2) = \sigma^2 \delta((z_1-z_2)-h). \quad (2.17)$$

Thus,

$$\begin{aligned} \int_0^\infty e^{i\tau h} \mathbb{E}X(t)X(t+h) dh &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^\infty dz_1 \int_0^\infty ds_1 \int_0^\infty ds_2 \int_0^\infty dz_2 s_1^{\beta-1} s_2^{\beta-1} \\ &\quad \times e^{-(s_1+s_2)\mu} h_\alpha(z_1, s_1) h_\alpha(z_2, s_2) e^{i\tau(z_1-z_2)}. \end{aligned}$$

By considering the characteristic function of a positively-skewed stable process with law h_α , we have that

$$\int_0^\infty e^{i\tau z_1} h_\alpha(z_1, s_1) dz_1 = e^{-(i\tau)^\alpha s_1} = e^{-s_1 |\tau|^\alpha e^{-i\frac{\pi}{2} \operatorname{sgn} \tau}}, \quad (2.18)$$

and

$$\int_0^\infty e^{-i\tau z_2} h_\alpha(z_2, s_2) dz_2 = e^{-(i\tau)^\alpha s_2} = e^{-s_2 |\tau|^\alpha e^{i\frac{\pi}{2} \operatorname{sgn} \tau}}. \quad (2.19)$$

Thus, we obtain that

$$\begin{aligned} & \int_0^\infty e^{i\tau h} \mathbb{E}X(t)X(t+h) dh \\ &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^\infty ds_1 \int_0^\infty ds_2 s_1^{\beta-1} s_2^{\beta-1} e^{-(s_1+s_2)\mu} e^{-(i\tau)^\alpha s_2 - (-i\tau)^\alpha s_1} \\ &= \frac{\sigma^2}{\left(\mu + |\tau|^\alpha e^{-i\frac{\pi}{2} \operatorname{sgn} \tau}\right)^\beta \left(\mu + |\tau|^\alpha e^{i\frac{\pi}{2} \operatorname{sgn} \tau}\right)^\beta} \\ &= \frac{\sigma^2}{\left(\mu^2 + 2|\tau|^\alpha \mu \cos \frac{\pi\alpha}{2} + |\tau|^{2\alpha}\right)^\beta}. \end{aligned} \quad \square$$

Remark 2.7. In the special case $\alpha = 1$ the result above simplifies and yields

$$f(\tau) = \frac{\sigma^2}{(\mu^2 + \tau^2)^\beta}. \quad (2.20)$$

We note that for $\beta = 1$, (2.20) becomes the spectral density of the Ornstein-Uhlenbeck process. Processes with the spectral density f are dealt with, for example, in [2] where also space-time random fields governed by stochastic equations are considered. The covariance function is given by

$$\begin{aligned} \operatorname{Cov}_X(h) &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{-i\tau h} f(\tau) d\tau \\ &= \frac{\sigma^2}{2\pi} \int_{\mathbb{R}} e^{-i\tau h} \left(\frac{1}{\Gamma(\beta)} \int_0^\infty z^{\beta-1} e^{-z\mu^2 - z\tau^2} dz \right) d\tau \\ &= \frac{\sigma^2}{\Gamma(\beta)} \int_0^\infty z^{\beta-1} e^{-z\mu^2} \left(\frac{1}{2\pi} \int_{\mathbb{R}} e^{-i\tau h - z\tau^2} d\tau \right) dz \\ &= \frac{\sigma^2}{\Gamma(\beta)} \int_0^\infty z^{\beta-1} e^{-z\mu^2} \frac{e^{-\frac{h^2}{4z}}}{\sqrt{4\pi z}} dz \\ &= \frac{\sigma^2}{2\Gamma(\beta)\Gamma(\frac{1}{2})} \int_0^\infty z^{\beta-\frac{1}{2}-1} e^{-z\mu^2 - \frac{h^2}{4z}} dz \\ &= \frac{\sigma^2}{\Gamma(\beta)\Gamma(\frac{1}{2})} \left(\frac{|h|}{2\mu} \right)^{\beta-\frac{1}{2}} K_{\beta-\frac{1}{2}}(\mu|h|), \quad h \geq 0 \end{aligned}$$

where K_ν is the modified Bessel function with integral representation given by

$$\int_0^\infty x^{\nu-1} \exp\{-\beta x^p - \alpha x^{-p}\} dx = \frac{2}{p} \left(\frac{\alpha}{\beta} \right)^{\frac{\nu}{2p}} K_{\frac{\nu}{p}} \left(2\sqrt{\alpha\beta} \right), \quad p, \alpha, \beta, \nu > 0 \quad (2.21)$$

(see for example [5], formula 3.478). We observe that $K_\nu = K_{-\nu}$ and $K_{\frac{1}{2}}(x) = \sqrt{\frac{\pi}{2x}} e^{-x}$. Moreover,

$$K_\nu(x) \approx \frac{2^{\nu-1} \Gamma(\nu)}{x^\nu} \quad \text{for } x \rightarrow 0^+ \quad (2.22)$$

([10, pag. 136]) and

$$K_\nu(x) \approx \sqrt{\frac{\pi}{2x}} e^{-x} \quad \text{for } x \rightarrow \infty. \quad (2.23)$$

Thus, we get that

$$\text{Cov}_X(h) \approx \mu^{1-2\beta}, \quad \text{for } h \rightarrow 0^+ \quad (2.24)$$

and

$$\text{Cov}_X(h) \approx \left(\frac{h}{\mu}\right)^\beta \frac{1}{h} e^{-\mu h}, \quad \text{for } h \rightarrow \infty. \quad (2.25)$$

We now study the covariance of (1.2). Recall that, a symmetric stable process S of order α with density g has the following characteristic function

$$\widehat{g}(\xi, t) = \mathbb{E} e^{i\xi S(t)} = e^{-\sigma^2 |\xi|^\alpha t}, \quad \alpha \in (0, 2].$$

Consider two independent stable processes $S_1(w)$, $S_2(w)$, $w \geq 0$, with $\sigma_1^2 = 1$ and $\sigma_2^2 = 2\mu \cos \frac{\pi\alpha}{2}$. Let $g_1(x, w)$, $x \in \mathbb{R}$, $w \geq 0$ and $g_2(x, w)$, $x \in \mathbb{R}$, $w \geq 0$ be the corresponding density laws. Then, the following result holds true.

Theorem 2.8. *The covariance function of (1.2) is*

$$\text{Cov}_X(h) = \frac{\sigma^2}{\Gamma(\beta)} \int_0^\infty w^{\beta-1} e^{-w\mu^2} \int_{-\infty}^{+\infty} g_1(h-z, w) g_2(z, w) dz dw \quad (2.26)$$

or

$$\text{Cov}_X(h) = \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E} g_{S_1+S_2}(h, W_\beta) \quad (2.27)$$

and W_β is a gamma r.v. with parameters μ^2, β .

Proof. Notice that

$$f(\tau) = \frac{\sigma^2}{\Gamma(\beta)} \int_0^\infty w^{\beta-1} e^{-w(\mu^2 + 2|\tau|^\alpha \mu \cos \frac{\pi\alpha}{2} + |\tau|^{2\alpha})} dw$$

where

$$e^{-2\mu \cos \frac{\pi\alpha}{2} |\tau|^\alpha w} = \mathbb{E} e^{i\tau S_2(w)} = \widehat{g}_2(\tau, w) \quad \text{and} \quad e^{-|\tau|^{2\alpha} w} = \mathbb{E} e^{i\tau S_1(w)} = \widehat{g}_1(\tau, w).$$

Thus,

$$f(\tau) = \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E} [\widehat{g}_1(\tau, W_\beta) \widehat{g}_2(\tau, W_\beta)]$$

from which, we immediately get that

$$\begin{aligned} \text{Cov}_X(h) &= \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E} \left[\int_{-\infty}^{+\infty} g_1(h-z, W_\beta) g_2(z, W_\beta) dz \right] \\ &= \frac{\sigma^2}{\Gamma(\beta)} \int_0^\infty w^{\beta-1} e^{-w\mu^2} \int_{-\infty}^{+\infty} g_1(h-z, w) g_2(z, w) dz dw \quad \square \end{aligned}$$

3 Fractional powers of higher-order operators

We focus our attention on the following equation

$$\left(\mu - \frac{d^2}{dt^2} \right)^\beta X(t) = \mathcal{E}(t), \quad \mu > 0, \beta > 0, t \in \mathbb{R} \quad (3.1)$$

that is, on the equation (1.4) for $n = 1$.

Theorem 3.1. A generalized m.s. solution to the equation (3.1) is

$$\begin{aligned} X(t) &= \frac{1}{\mu^\beta} \mathbf{E}[\mathcal{E}(t + Y_2(W_\beta))], \quad \beta > 0, \mu > 0 \\ &= \frac{1}{\Gamma(\beta)} \int_{-\infty}^{+\infty} \mathcal{E}(t+x) \int_0^\infty w^{\beta-1} e^{-\mu w} \frac{e^{-\frac{x^2}{4w}}}{\sqrt{4\pi w}} dw dx. \end{aligned} \quad (3.2)$$

Moreover, the spectral density of (3.2) reads

$$f(\tau) = \frac{\sigma^2}{(\mu + \tau^2)^{2\beta}} \quad (3.3)$$

and the corresponding covariance function has the form

$$\text{Cov}_X(h) = \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E} \left[\frac{e^{-\frac{h^2}{4W_{2\beta}}}}{2\sqrt{\pi W_{2\beta}}} \right] = \frac{\sigma^2}{\sqrt{\pi} \Gamma(2\beta)} \left(\frac{|h|}{2\sqrt{\mu}} \right)^{2\beta-\frac{1}{2}} K_{2\beta-\frac{1}{2}}(|h|\sqrt{\mu}). \quad (3.4)$$

Proof. We can formally write

$$e^{w \frac{d^2}{dt^2}} = \int_{-\infty}^\infty e^{x \frac{d}{dt}} \frac{e^{-\frac{x^2}{4w}}}{2\sqrt{\pi w}} dx \quad (3.5)$$

so that from (3.1) we have that

$$\begin{aligned} X(t) &= \frac{1}{\Gamma(\beta)} \int_0^\infty e^{-\mu w} w^{\beta-1} dw \int_{-\infty}^\infty \frac{e^{-\frac{x^2}{4w}}}{2\sqrt{\pi w}} e^{x \frac{d}{dt}} \mathcal{E}(t) dx \\ &= \frac{1}{\Gamma(\beta)} \int_0^\infty e^{-\mu w} w^{\beta-1} dw \int_{-\infty}^\infty \frac{e^{-\frac{x^2}{4w}}}{2\sqrt{\pi w}} \mathcal{E}(t+x) dx. \end{aligned} \quad (3.6)$$

By observing that, from (1.18),

$$\mathbb{E} \mathcal{E}(t+x_1) \mathcal{E}(t+h+x_2) = \sigma^2 \delta(h+x_2-x_1)$$

we can write

$$\begin{aligned} \mathbb{E} X(t) X(t+h) &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^\infty e^{-\mu w_1} w_1^{\beta-1} dw_1 \int_0^\infty e^{-\mu w_2} w_2^{\beta-1} dw_2 \int_{-\infty}^\infty \frac{e^{-\frac{x_1^2}{4w_1}}}{2\sqrt{\pi w_1}} \frac{e^{-\frac{(h-x_1)^2}{4w_2}}}{2\sqrt{\pi w_2}} dx_1 \\ &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^\infty e^{-\mu w_1} w_1^{\beta-1} dw_1 \int_0^\infty e^{-\mu w_2} w_2^{\beta-1} dw_2 \frac{e^{-\frac{h^2}{4(w_1+w_2)}}}{2\sqrt{\pi(w_1+w_2)}} \\ &= \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E} \left[\frac{e^{-\frac{h^2}{4(W_1+W_2)}}}{2\sqrt{\pi(W_1+W_2)}} \right] \\ &= \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E} \left[\frac{e^{-\frac{h^2}{4W_{2\beta}}}}{2\sqrt{\pi W_{2\beta}}} \right] \\ &= \frac{\sigma^2}{\Gamma(2\beta)} \int_0^\infty \frac{e^{-\frac{h^2}{4w}}}{2\sqrt{\pi w}} w^{2\beta-1} e^{-\mu w} dw \\ &= \frac{\sigma^2}{\sqrt{\pi} \Gamma(2\beta)} \left(\frac{h}{2\sqrt{\mu}} \right)^{2\beta-\frac{1}{2}} K_{2\beta-\frac{1}{2}}(h\sqrt{\mu}). \end{aligned}$$

We notice that

$$\text{Cov}_X(h) = \frac{\sigma^2}{\mu^{2\beta}} P(B(W_{2\beta}) \in dh) / dh$$

where $B(W_{2\beta})$ is a Brownian motion with random time $W_{2\beta}$. Thus, we obtain that

$$f(\tau) = \int_{-\infty}^{\infty} e^{i\tau h} \text{Cov}_X(h) dh = \frac{\sigma^2}{\Gamma(2\beta)} \int_0^{\infty} e^{-w\tau^2} w^{2\beta-1} e^{-\mu w} dw = \frac{\sigma^2}{(\mu + \tau^2)^{2\beta}}. \quad \square$$

An alternative representation of the process (3.2) can be also given in terms of the Bessel function K_ν . In particular, we observe that

$$X(t) = \frac{1}{\sqrt{\pi}\Gamma(\beta)} \int_{-\infty}^{+\infty} \mathcal{E}(t+x) \left(\frac{|x|}{2\sqrt{\mu}} \right)^{\beta-\frac{1}{2}} K_{\beta-\frac{1}{2}}(|x|\sqrt{\mu}) dx$$

The covariance function of (3.2) can be alternatively written as

$$\begin{aligned} \mathbb{E}X(t)X(t+h) &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^{\infty} e^{-\mu w_1} w_1^{\beta-1} dw_1 \int_0^{\infty} e^{-\mu w_2} w_2^{\beta-1} dw_2 \int_{-\infty}^{\infty} \frac{e^{-\frac{x_1^2}{4w_1}}}{2\sqrt{\pi w_1}} \frac{e^{-\frac{(x_1-h)^2}{4w_2}}}{2\sqrt{\pi w_2}} dx_1 \\ &= \frac{\sigma^2}{\pi\Gamma^2(\beta)} \int_{-\infty}^{+\infty} \left(\frac{|x_1||x_1-h|}{4\mu} \right)^{\beta-\frac{1}{2}} K_{\beta-\frac{1}{2}}(\sqrt{\mu}|x_1|) K_{\beta-\frac{1}{2}}(\sqrt{\mu}|x_1-h|) dx_1 \end{aligned}$$

where, in the last step we applied formula (2.21).

We now pass to the general even-order fractional equation (1.4).

Theorem 3.2. A generalized m.s. solution to the equation (1.4) is

$$\begin{aligned} X(t) &= \frac{1}{\mu^\beta} \mathbb{E}[\mathcal{E}(t + Y_{2n}(W_\beta))], \quad \beta > 0, \mu > 0 \\ &= \frac{1}{\Gamma(\beta)} \int_0^{\infty} w^{\beta-1} e^{-\mu w} \int_{-\infty}^{+\infty} u_{2n}(x, w) \mathcal{E}(t+x) dx dw. \end{aligned} \quad (3.7)$$

Moreover, the spectral density of (3.7) reads

$$f(\tau) = \frac{\sigma^2}{(\mu + \tau^{2n})^{2\beta}} \quad (3.8)$$

and the related covariance function becomes

$$\text{Cov}_X(h) = \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E}[u_{2n}(h, W_{2\beta})]. \quad (3.9)$$

Proof. The solution $u_{2n}(x, t)$ to

$$\frac{\partial}{\partial t} u_{2n} = (-1)^{n+1} \frac{\partial^{2n}}{\partial x^{2n}} u_{2n} \quad (3.10)$$

has Fourier transform

$$U(\beta, t) = e^{(-1)^{n+1}(-i\beta)^{2n}t} = e^{-\beta^{2n}t}. \quad (3.11)$$

We write

$$e^{-w \frac{\partial^{2n}}{\partial x^{2n}}} = \int_{-\infty}^{\infty} e^{ix \frac{\partial}{\partial t}} u_{2n}(x, w) dx. \quad (3.12)$$

Since

$$U(-i\beta, t) = e^{-(-1)^n \beta^{2n}t}, \quad (3.13)$$

we also write

$$e^{-w(-1)^n \frac{\partial^{2n}}{\partial t^{2n}}} = \int_{-\infty}^{\infty} e^{x \frac{\partial}{\partial t}} u_{2n}(x, w) dx. \quad (3.14)$$

In conclusion, we have that

$$X(t) = \left(\mu + (-1)^n \frac{\partial^{2n}}{\partial t^{2n}} \right)^{-\beta} \mathcal{E}(t) \quad (3.15)$$

$$\begin{aligned} &= \frac{1}{\Gamma(\beta)} \int_0^{\infty} dw e^{-\mu w} w^{\beta-1} \left(\int_{-\infty}^{+\infty} dx u_{2n}(x, w) e^{x \frac{\partial}{\partial t}} \mathcal{E}(t) \right) \\ &= \frac{1}{\Gamma(\beta)} \int_0^{\infty} dw e^{-\mu w} w^{\beta-1} \int_{-\infty}^{+\infty} dx u_{2n}(x, w) \mathcal{E}(t+x) \end{aligned} \quad (3.16)$$

and this confirms (3.7).

From (3.7), in view of (2.17), we obtain

$$\begin{aligned} \mathbb{E}X(t)X(t+h) &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^{\infty} dw_1 w_1^{\beta-1} e^{-\mu w_1} \int_0^{\infty} dw_2 w_2^{\beta-1} e^{-\mu w_2} \\ &\quad \cdot \int_{-\infty}^{+\infty} dx_1 u_{2n}(x_1, w_1) \int_{-\infty}^{+\infty} dx_2 u_{2n}(x_2, w_2) \delta(x_2 - x_1 + h) \\ &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^{\infty} dw_1 w_1^{\beta-1} e^{-\mu w_1} \int_0^{\infty} dw_2 w_2^{\beta-1} e^{-\mu w_2} \\ &\quad \cdot \int_{-\infty}^{+\infty} dx_1 u_{2n}(x_1, w_1) u_{2n}(x_1 - h, w_2) \\ &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^{\infty} dw_1 w_1^{\beta-1} e^{-\mu w_1} \int_0^{\infty} dw_2 w_2^{\beta-1} e^{-\mu w_2} u_{2n}(h, w_1 + w_2) \\ &= \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E}u_{2n}(h, W_1 + W_2). \end{aligned}$$

By following the same arguments as in the previous proof, we get that

$$\mathbb{E}X(t)X(t+h) = \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E}u_{2n}(h, W_{2\beta}) = \frac{\sigma^2}{\Gamma(2\beta)} \int_0^{\infty} dw w^{2\beta-1} e^{-\mu w} u_{2n}(h, w)$$

The spectral density of $X(t)$ is therefore

$$f(\tau) = \frac{\sigma^2}{\Gamma(2\beta)} \int_0^{\infty} dw w^{2\beta-1} e^{-\mu w - \tau^{2n} w} = \frac{\sigma^2}{(\mu + \tau^{2n})^{2\beta}}. \quad \square$$

Theorem 3.2 extends the results of Theorem 3.1 when even-order heat-type equations are involved.

We now pass to the study of the equation (1.9) for $n = 1$ and $\kappa = \mp 1$,

$$\left(\mu + \kappa \frac{d^3}{dt^3} \right)^{\beta} X(t) = \mathcal{E}(t), \quad \mu > 0, \beta > 0, t \in \mathbb{R}. \quad (3.17)$$

Theorem 3.3. A generalized solution to the equation (3.17) is

$$\begin{aligned} X(t) &= \frac{1}{\mu^{\beta}} \mathbf{E}[\mathcal{E}(t + Y_3(W_{\beta}))], \quad \beta > 0, \mu > 0 \\ &= \frac{1}{\Gamma(\beta)} \int_{-\infty}^{\infty} \mathcal{E}(t+x) \int_0^{\infty} w^{\beta-1} e^{-\mu w} \frac{1}{\sqrt[3]{3w}} \text{Ai}\left(\frac{\kappa x}{\sqrt[3]{3w}}\right) dw dx. \end{aligned} \quad (3.18)$$

Moreover, the covariance function

$$\text{Cov}_X(h) = \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E} \left[\frac{\sigma^2}{\sqrt[3]{3W_{2\beta}}} \text{Ai} \left(\frac{-\kappa h}{\sqrt[3]{3W_{2\beta}}} \right) \right] \quad (3.19)$$

where $\text{Ai}(x)$ is the Airy function has Fourier transform

$$f(\tau) = \frac{\sigma^2}{(\mu + i\kappa\tau^3)^{2\beta}}. \quad (3.20)$$

Proof. By following the approach adopted above, after some calculation, we can write that

$$X^-(t) = \frac{1}{\Gamma(\beta)} \int_0^\infty w^{\beta-1} e^{-\mu w + w \frac{d^3}{dt^3}} \mathcal{E}(t) dw \quad (3.21)$$

is the solution to

$$\left(\mu - \frac{d^3}{dt^3} \right)^\beta X(t) = \mathcal{E}(t) \quad (3.22)$$

whereas

$$X^+(t) = \frac{1}{\Gamma(\beta)} \int_0^\infty w^{\beta-1} e^{-\mu w - w \frac{d^3}{dt^3}} \mathcal{E}(t) dw \quad (3.23)$$

is the solution to

$$\left(\mu + \frac{d^3}{dt^3} \right)^\beta X(t) = \mathcal{E}(t) \quad (3.24)$$

The third-order heat type equation

$$\frac{\partial}{\partial t} u = \kappa \frac{\partial^3}{\partial x^3} u, \quad u(x, 0) = 0, \quad (3.25)$$

has solution, for $\kappa = -1$,

$$u(x, t) = \frac{1}{\sqrt[3]{3t}} \text{Ai} \left(\frac{x}{\sqrt[3]{3t}} \right), \quad x \in \mathbb{R}, t > 0, \quad (3.26)$$

with Fourier transform

$$\int_{-\infty}^\infty e^{i\beta x} u(x, t) dx = e^{-it\beta^3}. \quad (3.27)$$

Formula (3.27) leads to the integral

$$\int_{-\infty}^\infty e^{\theta x} u(x, t) dx = e^{t\theta^3}, \quad \theta \in \mathbb{R}$$

because of the asymptotic behaviour of the Airy function (see [1] and [11]). The solution to (1.9) with $n = 1$ (that is $\kappa = -1$) is therefore (3.21).

The equation (3.25) has solution, for $\kappa = +1$, given by

$$u(x, t) = \frac{1}{\sqrt[3]{3t}} \text{Ai} \left(\frac{-x}{\sqrt[3]{3t}} \right), \quad x \in \mathbb{R}, t > 0. \quad (3.28)$$

Thus, by following the same reasoning as before, we arrive at

$$\int_{-\infty}^\infty e^{\theta x} u(x, t) dx = e^{-t\theta^3}, \quad \theta \in \mathbb{R}$$

and we obtain that (3.23) solves (3.17) with $\kappa = +1$ is (3.23).

In light of (2.17) we get

$$\begin{aligned}\mathbb{E}[X^-(t) X^-(t+h)] &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^\infty e^{-\mu w_1} dw_1 w_1^{\beta-1} \int_0^\infty e^{-\mu w_2} dw_2 w_2^{\beta-1} \\ &\quad \cdot \int_{-\infty}^\infty \frac{1}{\sqrt[3]{3}w_1} \text{Ai}\left(\frac{x_1}{\sqrt[3]{3}w_1}\right) \frac{1}{\sqrt[3]{3}w_2} \text{Ai}\left(\frac{x_1-h}{\sqrt[3]{3}w_2}\right) dx_1 \\ &= \frac{\sigma^2}{\Gamma^2(\beta)} \int_0^\infty e^{-\mu w_1} dw_1 w_1^{\beta-1} \int_0^\infty e^{-\mu w_2} dw_2 w_2^{\beta-1} \\ &\quad \cdot \frac{1}{\sqrt[3]{3}(w_1+w_2)} \text{Ai}\left(\frac{h}{\sqrt[3]{3}(w_1+w_2)}\right) \\ &= \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E}\left[\frac{1}{\sqrt[3]{3}W_{2\beta}} \text{Ai}\left(\frac{h}{\sqrt[3]{3}W_{2\beta}}\right)\right].\end{aligned}$$

From the Fourier transform (3.27), we get that

$$\begin{aligned}f^-(\tau) &= \frac{\sigma^2}{\mu^{2\beta}} \int_{\mathbb{R}} e^{i\tau h} \mathbb{E}\left[\frac{1}{\sqrt[3]{3}W_{2\beta}} \text{Ai}\left(\frac{h}{\sqrt[3]{3}W_{2\beta}}\right)\right] dh \\ &= \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E}\left[e^{-i\tau^3 W_{2\beta}}\right] \\ &= \frac{\sigma^2}{(\mu + i\tau^3)^{2\beta}} \\ &= \frac{\sigma^2 e^{-i2\beta \arctan \frac{\tau^3}{\mu}}}{(\mu^2 + \tau^6)^\beta}.\end{aligned}$$

Also, we obtain that

$$\mathbb{E}[X^+(t) X^+(t+h)] = \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E}\left[\frac{1}{\sqrt[3]{3}W_{2\beta}} \text{Ai}\left(\frac{-h}{\sqrt[3]{3}W_{2\beta}}\right)\right].$$

with Fourier transform

$$f^+(\tau) = \frac{\sigma^2}{(\mu - i\tau^3)^{2\beta}} = \frac{\sigma^2 e^{+i2\beta \arctan \frac{\tau^3}{\mu}}}{(\mu^2 + \tau^6)^\beta}. \quad (3.29)$$

□

Theorem 3.4. A generalized m.s. solution to the equation (1.9) is

$$\begin{aligned}X(t) &= \frac{1}{\mu^\beta} \mathbb{E}[\mathcal{E}(t + Y_{2n+1}(W_\beta))], \quad \beta > 0, \mu > 0 \\ &= \frac{1}{\Gamma(\beta)} \int_0^\infty w^{\beta-1} e^{-\mu w} \int_{-\infty}^{+\infty} u_{2n+1}(\kappa x, w) \mathcal{E}(t+x) dw dx.\end{aligned}$$

Moreover, the covariance function

$$\text{Cov}_X(h) = \frac{\sigma^2}{\mu^{2\beta}} \mathbb{E} u_{2n+1}(\kappa h, W_{2\beta})$$

has Fourier transform

$$f(\tau) = \frac{\sigma^2}{(\mu + i\kappa\tau^{2n+1})^{2\beta}} = \frac{\sigma^2 e^{-i2\beta\kappa \arctan \frac{\tau^{2n+1}}{\mu}}}{(\mu^2 + \tau^{2(2n+1)})^\beta}.$$

Proof. The proof follows the same lines as in the previous theorem. □

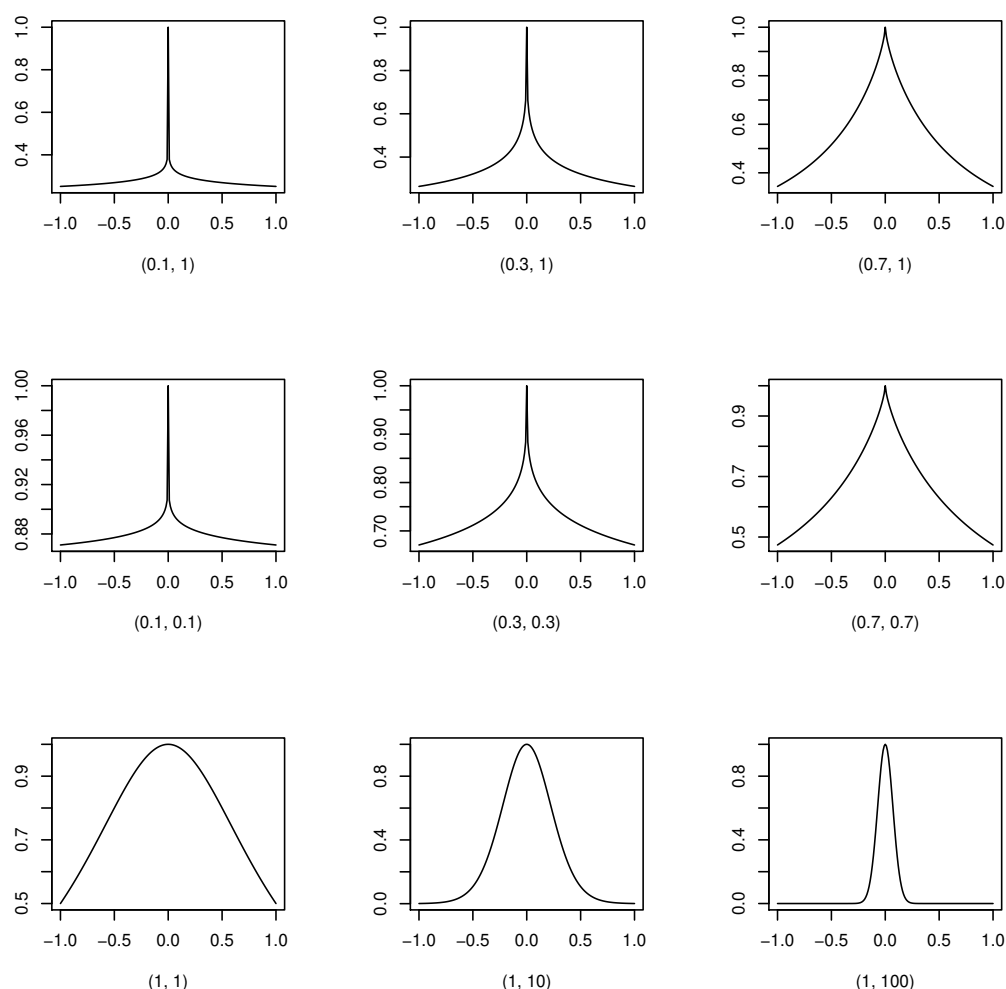


Figure 1: The spectral density (1.3) with different values for the parameters (α, β) .

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