Comparative Analysis of Finite Field-dependent BRST Transformations

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Abstract—We review our recent study [1–6], introducing the concept of finite field-dependent BRST and BRST-antiBRST transformations for gauge theories and investigating their properties. An algorithm of exact calculation for the Jacobian of a respective change of variables in the path integral is presented. Applications to the Yang–Mills theory, in view of infra-red (Gribov) peculiarities, are discussed.

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1. INTRODUCTION

BRST transformations [7, 8] for gauge theories in Lagrangian formalism were first examined in the capacity of field-dependent (FD) BRST transformations within the field-antifield approach [9] in order to prove the independence from small gauge variations (expressed through the gauge fermion \( \psi \)) of the path integral:

\[
Z_{\psi} = Z_{\psi + \delta \psi}, \quad \text{with the choice } \mu = -\frac{1}{\hbar} \delta \psi
\]

for the Grassmann-odd parameter of FD BRST transformations. Originally introduced as the case of a special SUSY transformation, being a change of the field variables:

\[
\phi^A \rightarrow \phi'^A = \phi^A + \delta_\mu \phi^A,
\]

the integrand \( \mathcal{J}_\psi \) with a quantum action \( S_\psi(\phi) \), BRST transformations were extended, by means of antiBRST transformations [10, 11] in Yang–Mills theories, to \( N = 2 \) BRST-antiBRST transformations (in Yang–Mills [12] and general gauge theories [13]), which were associated with an Sp(2)-doublet of Grassmann-odd parameters, \( \mu_a, a = 1, 2 \).

The concept of finite FD BRST transformations was introduced [14] in Yang–Mills theories, as a sequence of infinitesimal FD BRST transformations, in order to prove the gauge-independence of the path integral within the family of \( R_\xi \)-gauges and their nonlinear deformations in the field variables. The authors of [15] suggested an analysis of so-called soft BRST symmetry breaking in Yang–Mills theories, with reference to the Gribov problem [16] in the long-wave spectra of field configurations, which also involves the Zwanziger proposal [17] for a horizon functional joined additively to a BRST invariant quantum action. The study of [18] investigated the scope of problems related to [15] in the field-antifield formalism and suggested an equation for the BRST non-invariant addition \( M(\phi, \phi^*) \) to the quantum action \( S_\psi(\phi, \phi^*) \) of a general gauge theory. The validity of this equation preserves the gauge-independence of the corresponding vacuum functional \( Z_{\psi, M}(0) \), see (4) for a definition,

\[
\mathcal{J}_{\psi} = d\phi \exp \left\{ \frac{\hbar}{\alpha} S_\psi(\phi) \right\}, \quad Z_{\psi, M}(J, \phi^*) = 0,
\]

where it is assumed that \( [M_A^a, M^{*A}_b] = [M^a, M^{*A}] \). In terms of the vacuum expectation value, in the presence of external sources \( J_A \), and with a given gauge \( \psi \), relation (2) acquires the form:

\[
\delta S_{\psi, M} = \delta \phi^A S_\psi
\]

\[
\left\{ \delta M + M^a \delta \phi^A \right\} \delta \psi(\phi) = \left\{ \delta M - M^a \delta \mu(\delta \psi) \right\} = 0,
\]

where \( \delta \) is the generator of BRST transformations.
attempted to use FD BRST transformations [14] for relating the vacuum functionals in YM and GZ (Gribov–Zwanziger) theories under different gauges. An explicit calculation of the functional Jacobian for a change of variables induced by FD BRST transformations in YM theories with a finite parameter $\mu$ was made in [20], to establish the gauge-independence of $Z_{\psi,M}$ under a finite change of the gauge, $\psi \to \psi + \Delta \psi$, and afterwards in [21], to solve equation (3), with $H(\phi, \phi^*) = H(\phi)$ for GZ theory, in a way different from anticanonical transformations, as compared to [18].

The present article reviews the study of finite BRST and BRST-antiBRST (special $N = 1, 2$ SUSY) transformations (including the case of field-dependent parameters), and the way they influence the properties of the quantum action and path integral in conventional quantization. We use the DeWitt condensed notation and the conventions of [1, 2], e.g., we use $\epsilon^2$ for the value of Grassmann parity of a quantity $F$.

Derivatives with respect to (anti)field variables $\phi^A, \phi^*_A$ and sources $J_A$ are denoted by $\partial_A, (\partial^*_A)$ and $\partial^{(A)}$, the raising and lowering of Sp(2) indices, $(s, s^*) = (e^{ab} s_b, e_{ab} s^b)$, are carried out by a constant antisymmetric tensor $e^{ab}, e^{*ab} e_{cb} = \delta^a_b, e^{12} = 1$.

### 2. PROPOSALS FOR FINITE BRST TRANSFORMATIONS

The problem of softly broken BRST symmetry (SB BRST) in general gauge theories was solved in [1] on a basis of finite FD BRST transformations (invariance transformations for the integrand in (4) at $J = M = 0$) with finite odd-valued parameters $\mu(\phi, \phi^*)$ depending on external antifields $\phi^*_A$, $\epsilon(\phi^*_A) + 1 = \epsilon(\phi^A) = \epsilon_A$, and internal fields $\phi^A$ whose contents include the classical fields $A^i, i = 1, \ldots, n$, with gauge transformations $\delta A^i = R^i_\alpha(A) \xi^\alpha$, $\alpha = 1, \ldots, m < n$, the ghost, antighost, and Nakanishi–Lautrup fields $C^a, \bar{C}^a, B^a, \bar{B}^a, (e_A, \bar{e}_A, C^a, \bar{C}^a, B^a) = (e_i, e^{\alpha}, e_\alpha + 1, e_\alpha + 1, e_\alpha)$, as well as the additional towers of fields depending on the (ir)reducibility of the theory. The generating functional of Green’s functions depending on external sources $J_A, \epsilon(J_A) = \epsilon_A$, with an SB BRST symmetry term $M, \epsilon(M) = 0$, is given by

$$Z_{\psi,M}(\phi, \phi^*) = \int d\phi \exp \left[ \frac{1}{\hbar} S_{\psi}(\phi, \phi^*) \right]$$

$$+ M(\phi, \phi^*) + J_A \phi^*_A,$$

$$S_{\psi} = \partial_A \bar{\gamma}^*_A S_{\psi} = \partial_A \phi^*_A,$$

where the generator $\bar{\gamma}_A$ reduces at $\phi^* = 0$ to the usual generator $\bar{\gamma}$ of (FD) BRST transformations, $\partial_A \phi^* = S^*_A(\phi, 0) \mu$, and fails to be nilpotent, $(\bar{\gamma}_A)^2 = \partial_A S_{\psi}(\phi, 0) S_{\psi}^* \neq 0$, due to the quantum master equation for $S_{\psi}$, $\Delta \exp \left[ \frac{1}{\hbar} S_{\psi} \right] = 0$, with $\Delta = (-1)^{\epsilon_a} \partial_A \phi^* A^A$.

The construction of finite BRST-antiBRST Lagrangian transformations solving the same problem within a suitable quantization scheme (starting from YM theories), is problematic in view of the BRST-antiBRST non-invariance of the gauge-fixed quantum action $S_F$, in a form more than linear in $\mu_\alpha$, $S_F(g, (\mu, \mu^*)) = S_F(\phi) + O(\mu, \mu^*)$, with the gauge condition encoded by a gauge boson $F(\phi)$. This problem was solved by finite BRST-antiBRST transformations in a group form, $\{g(\mu, \mu^*)\}$, using an appropriate set of variables $\Gamma^p$, according to [2]

$$\{G(g(\mu, \mu^*)) = G(\Gamma) \} \Rightarrow g(\mu, \mu^*)$$

$$= 1 + \bar{\gamma}_A \mu^A + \frac{1}{4} \bar{\gamma}^*_A \partial^*_A \mu^2 \exp \left[ \bar{\gamma}^*_A \mu^2 \right],$$

where $G$ is a certain functional with the indicated conditions, $\mu^2 \equiv \mu^A \mu^A$, and $\bar{\gamma}^*_A \bar{\gamma}^A = \bar{\gamma}^*_A \bar{\gamma}^A$ are the generators of BRST-antiBRST and mixed BRST-antiBRST transformations in the space of $\Gamma^p$. These transformations, however, cannot be presented as group elements (in terms of an exp-like relation) for an Sp(2) doublet $\mu$ which is not closed under BRST-antiBRST transformations: $\mu, \bar{\gamma}_b \neq 0$.

In YM theories, the construction of finite $N = 2$ BRST transformations (5) is straightforward [2] and uses the explicit form of BRST-antiBRST generators [13] in the space of fields $\phi^A = (A^a, C^a, \bar{C}^a, B^a)$ arranged into Sp(2)-symmetric tensors, $(A^a, C^a, B^a) = (A^{i, j}, C^a, B^a)$.

In general gauge theories, such as reducible ones or those with an open gauge algebra, the corresponding space of triplectic variables $\Gamma^p_r \equiv (\phi^A, \phi^*_A, \bar{\phi}_A, \bar{\phi}^*_A, \bar{\pi}^*_A, \lambda^A)$ in the Sp(2)-covariant Lagrangian quantization scheme [13] contains, in addition to $\phi^A$, 3 sets of antifields $\phi^*_A, \bar{\phi}_A, \epsilon(\phi^*_A, \bar{\phi}_A) = (\epsilon_A + 1, \epsilon_A)$, for BRST, antiBRST and mixed BRST-antiBRST transformations, and 3 sets of Lagrangian multipliers $\pi^*_A, \lambda^A, \epsilon(\pi^*_A, \lambda^A) = (\epsilon_A + 1, \epsilon_A)$, introducing the

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gauge. The corresponding generating functional of Green's functions, $Z_F(J)$,
\[
Z_F(J) = \int d\Gamma \exp \left\{ \left( \frac{1}{\hbar} \right) \left[ \mathcal{L} + \frac{1}{2} F \mathcal{U} + J \right] \right\} ,
\]
\[
\mathcal{U}^a = s^a \mathcal{A}^a + e^{ab(\pi \chi)} A^b A^a ,
\]
is invariant, at $J = 0$, with respect to finite $N = 2$ BRST transformations (for constant $\mu$) in the space of $\Gamma^p$, which are given by (5) with a functional $\Gamma^p = G(\Gamma^p)$:
\[
\Gamma^p \rightarrow \Gamma^p = \Gamma^p \left( 1 + \frac{1}{4} \right)^{\frac{1}{4}} \frac{2}{\sqrt{2}} \frac{1}{2} \mu \mathcal{A}^a \left( 1 + \frac{1}{4} \right)^{\frac{1}{4}} \frac{2}{\sqrt{2}} \frac{1}{2} \mu \mathcal{A}^a ,
\]
\[
\Gamma_{tr} g(\mu) \rightarrow \Gamma_{tr} g(\mu) = \mathcal{A}_{tr} F_{tr} ,
\]
where
\[
\mathcal{A}^a = \left( \partial_{\mathcal{A}} A^a , \mathcal{A}_{tr} , O_{tr} , O_{tr} \right) (\mathcal{A}^a , S_A (-1)^{s_A} ,
\]
\[
\mathcal{A}^a = (1 + \frac{1}{4} \mu \mathcal{A}^a ) \mathcal{A}^a (1 + \frac{1}{4} \mu \mathcal{A}^a ) ,
\]
provided that
\[
\mathcal{A}^a = (1 + \frac{1}{4} \mu \mathcal{A}^a ) \mathcal{A}^a (1 + \frac{1}{4} \mu \mathcal{A}^a ) ,
\]
and reduces, in a rank-1 theory with a closed gauge algebra, $[\Delta s_A , s_A ] = [0, 0]$, where $s_A = \mathcal{A}^a$, to the form
\[
\mathcal{A}^a = \left( 1 + \frac{1}{4} \mu \mathcal{A}^a \right)^{-1} ,
\]
which is the same as in YM theories. The Jacobian (9) allows one to solve the problem of SB BRST symmetry in general gauge theories [1] and was examined in detail [5] for an equivalent representation of $Z_{YM}(J, \phi^*)$ with BRST transformations $\Gamma^p \rightarrow \Gamma^p = \Gamma^p (1 + \frac{1}{4} \mu \mathcal{A}^a ) \mathcal{A}^a (1 + \frac{1}{4} \mu \mathcal{A}^a )$, for $\mu(\Gamma)$ and $\Gamma^p s = (\phi^A , \phi^* , \lambda^A , \tilde{s}) = (\lambda^A , S_{\partial A} , 0)$, in an extended space $\Gamma^p$ of fields $\phi^A$, internal antifields $\phi^*_{\partial A}$, and Lagrangian multipliers $\lambda^A$ to Abelian hypergauge conditions, $G_A (\phi, \phi^*) = \phi^* - \psi(\phi) \partial_A A$, with the result given by
\[
\exp \left[ \frac{\mathcal{A}^a + \mathcal{A}^a}{\mu} \right] = (1 + \frac{1}{4} \mu \mathcal{A}^a )^{-1} [1 + (\Delta S_{\phi^*})] + O(\mu^3 \mathcal{A}^a) .
\]
3 In the case $\mu \mathcal{A}^a \neq 0$, the set $(\phi^a)_{\mu}$, for $\phi = \phi^a (\mu)$, cannot be presented as Lie group elements: $g(\mu) \neq \exp (\mathcal{A}_{\mu} \mathcal{A}^a)$.

\[
\text{Sdet} \begin{bmatrix} \Gamma^p s = (\phi^A , \phi^* , \lambda^A , \tilde{s}) = (\lambda^A , S_{\partial A} , 0) \end{bmatrix} \]
\[
= \frac{1}{(1 + \frac{1}{4} \mu \mathcal{A}^a )^{-1} [1 + (\Delta S_{\phi^*})] + O(\mu^3 \mathcal{A}^a) .}
\]

For BRST-antiBRST transformations in YM theories, the technique of calculating the Jacobian was first examined for functionally-dependent parameters $\mu = \Lambda(\mu) \tilde{s}$ with an even-valued functional $\Lambda$ and was developed in [2]. The result is given by,
\[
\exp \left[ \frac{\mathcal{A}^a + \mathcal{A}^a}{\mu} \right] = (1 + \frac{1}{4} \mu \mathcal{A}^a )^{-1} \mathcal{A}^a [1 + (\Delta S_{\phi^*})] + O(\mu^3 \mathcal{A}^a) .
\]

\[
\text{Sdet} \begin{bmatrix} \Gamma^p s = (\phi^A , \phi^* , \lambda^A , \tilde{s}) = (\lambda^A , S_{\partial A} , 0) \end{bmatrix} \]
\[
= \frac{1}{(1 + \frac{1}{4} \mu \mathcal{A}^a )^{-1} [1 + (\Delta S_{\phi^*})] + O(\mu^3 \mathcal{A}^a) .}
\]

\[
\exp \left[ \frac{\mathcal{A}^a + \mathcal{A}^a}{\mu} \right] = (1 + \frac{1}{4} \mu \mathcal{A}^a )^{-1} \mathcal{A}^a [1 + (\Delta S_{\phi^*})] + O(\mu^3 \mathcal{A}^a) .
\]
where \((e)^a \) and tr denote \(\delta_a^b \) and trace over \(\text{Sp}(2) \) indices. The Jacobian (15) is generally not BRST-anti-BRST exact; however, it reduces at \(\mu_a = \Lambda \tilde{s}_a \) to the Jacobian (14), due to

\[
\text{tr} m^a = \text{tr}(\Lambda \tilde{s}_a \tilde{s}^a) = -(1/2)\text{tr} \delta_a^b \Lambda \tilde{s}_b^2
\]

\[
\Rightarrow \text{tr} m^a = 2 - (1/2)\Lambda \tilde{s}_a^2 \Rightarrow J_{\mu_a} = J_{\Lambda \tilde{s}_a}.
\]

In general gauge theories (6)–(8), the calculation of Jacobians induced by FD BRST-antiBRST transformations was first carried out in [3, 5] with functionally-dependent parameters \(\mu_a = \Lambda(\phi, \pi, \lambda) \tilde{U}_a \), the restricted generators \(\tilde{U}_a = \tilde{s}^a |_{\phi, \pi, \lambda} \) satisfying the algebra \(\{\tilde{U}_a, \tilde{U}_b\} = 0\), and afterwards in [6] with arbitrary parameters \(\mu_a(\Gamma_{\mu})\), including functionally-independent \(\mu_a(\phi, \pi, \lambda)\). The result is given by

\[
J_{\Lambda \tilde{s}_a} = \text{Sdet} \left[ \Gamma^b_{\Lambda \tilde{g}}(\Lambda \tilde{U}_a) \right] \tilde{U}_b^a = \exp \left[ -\left( \frac{1}{4} \Delta^a \tilde{s}_a \right) \right] \frac{1}{4} \left( 1 - \frac{1}{2} \Lambda \tilde{s}_a^2 \right)^{-1},
\]

\[
J_{\mu_a} = \exp \left[ -\left( \frac{1}{4} \Delta^a \tilde{s}_a \right) \right] \frac{1}{4} \left( 1 - \frac{1}{2} \Lambda \tilde{s}_a^2 \right)^{-1},
\]

\[
J_{\mu_a(\Gamma_{\mu})} = J_{\mu_a(\Gamma_{\mu})} \times \exp \left[ \frac{1}{4} \left( \frac{1}{4} \Delta^a \tilde{s}_a \right) \left( e + m \right) \right] \times \exp \left[ \frac{1}{4} \left( \frac{1}{4} \Delta^a \tilde{s}_a \right) \left( e + m \right) \right] \times \exp \left[ \frac{1}{4} \left( \frac{1}{4} \Delta^a \tilde{s}_a \right) \left( e + m \right) \right]
\]

The second multiplier in (19) draws a difference between the Jacobians \(J_{\mu_a(\phi, \pi, \lambda)}\) and \(J_{\mu_a(\Gamma_{\mu})}\) because \(\tilde{s}_a\) are not reduced to the nilpotent \(\tilde{U}_a\) as they act on \(\Gamma_{\mu}\).

In generalized Hamiltonian formalism, the Jacobians of corresponding FD BRST-antiBRST transformations were calculated from first principles by the rules (11)–(15) in [4, 6].

4. IMPLICATIONS OF FINITE BRST TRANSFORMATIONS

For FD parameters, finite BRST transformations allow one to obtain a new form of the Ward identity and to establish the gauge-independence of the path integral under a finite change of the gauge, \(\psi \to \psi + \psi'\), provided that the SB BRST symmetry term \(M = M_\psi\) transforms to \(M_{\psi'\psi'} = M_\psi (1 + \tilde{s} \mu_\psi(\psi'))\), with \(\mu_\psi(\psi')\) being a solution of a so-called compensation equation:

\[
Z_{\psi, \mu_\psi}(0, \phi') = Z_{\psi'\psi', \mu_\psi(\psi')} (0, \phi')
\]

\[
\Rightarrow \psi'(\phi, \lambda) |_{\mu_\psi(\psi')} = \frac{i}{\hbar} \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n} (\mu_\psi(\psi'))^{-1} \mu_\psi(\psi'), \quad (20)
\]

The Ward identity, depending on the FD parameter \(\mu_\psi(\psi') = -\frac{i}{\hbar} g(y) \psi'\), for \(g(y) = 1 - \exp\{y/\hbar\}, \ y \equiv (i/\hbar) \psi' \tilde{s}_a\), and the gauge-dependence problem are described by the respective expressions [5]

\[
\left\{ 1 + \frac{i}{\hbar} J_{\phi} \frac{\delta}{\delta \mu_\psi(\psi')} \right\}_{\psi, \mu_\psi(\psi')} = 1, \quad (21)
\]

and \(\left\{ J_{\phi} \mu_\psi(\psi') \right\}_{\psi, \mu_\psi(\psi')} = 0\), as one makes averaging with respect to \(Z_{\psi, \mu_\psi(\psi')}(J, \phi')\). The above equations are equivalent to those of [1, 18].

FD BRST-antiBRST transformations solve the same problem under a finite change of the gauge, \(F \to F + F'\), provided that the SB BRST-antiBRST symmetry term \(M_F\) transforms to \(M_{F+F'} = M_F (1 + \tilde{s} \mu_\mu F' + \frac{1}{4} \tilde{s}^2 F')\), with \(\mu_\mu(\phi, \pi, \lambda) = \Lambda \tilde{U}_a\) being a solution to the corresponding compensation equation based on (6):

\[
Z_F(0) = Z_{F+F}(0) \Rightarrow F'(\phi, \pi, \lambda) |_{\mu_\mu(\phi, \pi, \lambda)} = 4 \hbar \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n} \left( \Lambda \tilde{U}_a \right)^{n-1} \Lambda, \quad (22)
\]

As a result, the corresponding Ward identity, with the FD parameters \(\mu_\mu(\phi, \pi, \lambda) = \frac{i}{2\hbar} g(y) F', \Lambda(\Gamma | F') = \frac{i}{2\hbar} g(y) F'\), for \(y \equiv (i/\hbar) F' \tilde{s}_a\), and the gauge-dependence problem acquire the form [5]

\[
\left\{ 1 + \frac{i}{\hbar} J_{\phi} \frac{\delta}{\delta \mu_\mu(\phi, \pi, \lambda)} \right\}_{F,F'} = 1,
\]

\[
Z_{F+F}(J) = Z_F(J) \left[ 1 + \frac{i}{\hbar} J_{\phi} \frac{\delta}{\delta \mu_\mu(\phi, \pi, \lambda)} \right] + \frac{1}{4} \tilde{s}^2 \left( \mu_\mu(\phi, \pi, \lambda) \right)^2 (\Gamma - F') \times \frac{i}{2\hbar} J_{\phi} \left[ \frac{\delta}{\delta \mu_\mu(\phi, \pi, \lambda)} \right] (\phi^a \tilde{U}_a) \mu_\mu(\phi, \pi, \lambda) |_{\mu_\mu(\phi, \pi, \lambda)} = 0, \quad (24)
\]

with a source-dependent average expectation value with respect to \(Z_F(J)\) corresponding to a gauge-fixing \(F(\phi)\).

By choosing the \(N = 1\) or \(N = 2\) SB BRST symmetry term \(M(\phi)\) as the horizon functional \(H(A)\) in Landau gauge and assuming the gauge-independence of
under a finite change of the gauge condition, \( \psi \rightarrow \psi + \psi' \) or \( F \rightarrow F + F' \), one can determine the functional \( H(A) \) in a new reference frame, \( \psi + \psi' \) or \( F + F' \), of the respective \( N = 1, 2 \) BRST symmetry setting, with account taken of (20), (22):

\[
H_{\psi'}(\phi) = H(A)\left[1 + \tilde{s}\mu(\psi')\right] \quad \text{or} \\
H_{F'}(\phi) = H(A)\left[1 + \tilde{s}^2\mu(\phi') + \frac{1}{4}\tilde{s}^2\mu^2(\phi')\right].
\] (25)

Notice in conclusion that the above \( N = 1, 2 \) FD BRST transformations make it possible to study their influence on the Yang–Mills, Gribov–Zwanziger, Freedman–Townsend models, and the Standard Model, as well as on the concept of average effective action [1–3, 5, 6].

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