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Review Article

REVISED FINITE FIELD-DEPENDENT BRST FORMULATION

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ABSTRACT

We present a simplified version of well-known finite field-dependent Becchi-Rouet-Stora-Tyutin (FFBRST) formulation advocated originally in Ref. [1]. In the present approach we don't require any ansatz for local functional in order to compute the Jacobian corresponding to functional measure which satisfies certain boundary conditions. We show the equivalence of our approach to the original one, by producing the same results obtained by the original method, in two explicit examples. In the first example, we build the connections between Lorentz and axial gauges in Yang-Mills theory. However, in the second example, we relate the covariant and non-covariant gauges of the Abelian antisymmetric rank-2 tensor field theory.

Key words: Symmetry, Gauge theory,

1. INTRODUCTION

Electromagnetic, weak and strong interactions are described by the standard model which is based on a non-Abelian gauge theory known as Yang-Mills (YM) theory [2]. Practical calculations in YM theory require a gauge choice. Although, many possibilities are available for the gauge condition, the Lorentz-type gauges and axial-type gauges are two most popular choices. The Lorentz-type gauges, when dealing with the singularities of the propagators, have the natural advantage of covariance and easy handling of Feynman rules [3]. The major disadvantage of Lorentz-type gauges is requirement of a ghost action which eventually makes the calculations more complex [4]. To get rid of this situation, different set of gauge; namely, the axial gauge has often been opted. The natural advantage of axial gauge is that the ghost parts of the effective action are trivial which simplifies the calculations considerably [5]. On the other hand, the Abelian antisymmetric 2-form theory [6, 7] is a model of singular gauge systems in which few constraints are dependent and therefore reducible. Within quantization of such reducible system, the gauge fixing term consisting the 2-form field remains itself invariant under a (secondary) gauge transformation which requires further (commuting) ghost fields (so-called ghost of ghosts) in order to remove complete redundancies of gauge freedom. Being a gauge theory, the 2-form gauge field theory plays a central role in analysing the classical strings [7], the whirlpool motion of an irrotational, incompressible fluid [8, 9]. It also explores the dual formulation in the Higgs models [10, 11]. The higher-form fields are very important ingredients of supergravity multiplets [12] as well as of the excited states in superstring theories [13, 14].

Incidentally, the introduction of a gauge fixing condition breaks the gauge symmetry of the theory. However, it was found by Becchi, Rouet and Stora [15] and Tyutin [16], that the action of the theory still enjoys a remaining symmetry, called the BRST symmetry. The BRST method is a very strong practical tool to handle the gauge theories. In particular, it helps in the renormalization as well as in proof of unitarity of the theories [15-18]. The generalized BRST symmetry, known as finite field-dependent BRST (FFBRST) transformation, was discussed originally by Joglekar and Mandal [1], which has found many interesting applications in diverse area [19-33]. A rather different approach to generalize the BRST transformation has also been studied [34, 35]. Moshin and Reshetnyak first time in Ref. [36] introduces the BRST-antiBRST transformations in YM theories in order to deal the case of quadratic parameter dependence. Further investigation on BRST-antiBRST transformations on general gauge theories has also been made in Refs. [37, 38], whereas Ref. [40] generalizes the parameters to the case of (arbitrary) fermionic field-dependent parameters [36–38]. The N = 1, 2 supersymmetries are also generalized in this framework [39].

In this review article, we revisit the FFBRST transformation in the original way. Furthermore, we evaluate the Jacobian corresponding to the path integral measure under FFBRST symmetry transformation. Here we find that the form of Jacobian has explicit dependence on the (infinitesimal) field-dependent parameter. In this approach we don't require any kind of local functional (S_1) which satisfies particular boundary conditions. Also, the exact form for local functional can be obtained only by solving some differential equation with initial boundary conditions (for details, see Ref. [1]). We show that FFBRST transformation developed in this article

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plays exactly the same role as by original FFBRST transformation but rather simply. We establish results by showing connection between covariant and non-covariant gauges for both the (non-Abelian) 1-form and (Abelian) 2-form gauge theories. But our formulation is not limited to these two cases only. One can compute all results of the original formulation by presently developed formulation.

2. FFBRST TRANSFORMATION

Here, we revisit the FFBRST transformation and evaluate the Jacobian corresponding to the path integral measure under FFBRST transformation in simpler way. In this approach, we don't require a (local) functional (S_1) which satisfies particular boundary conditions as in Ref. [1]. One can compute all results of the original formulation by presently developed formulation. For this purpose, we begin by writing the BRST symmetry for the collective field $\varphi(x)$ as follows:

$$\varphi'(x) - \varphi(x) = s_b\varphi(x)\,\Lambda\,. \tag{1}$$

Here $s_b\varphi(x)$ denotes the Slavnov variation and Λ refers to the anticommuting (global) transformation parameter.

Now, we interpolate a continuous parameter $\kappa(0 \leq \kappa \leq 1)$ to the fields $\varphi(x)$ so that $\varphi(x,\ \kappa = 0\,)$ corresponds to the original field and $\varphi(x,\ \kappa = 1) = \varphi(x) + s_b\varphi(x)\ \Theta(\varphi)$ refers the FFBRST transformed field characterized by field-dependent parameter $\Theta(\varphi)$. The FFBRST symmetry transformation can be justified by following infinitesimal field-dependent BRST symmetry transformation:

$$\frac{d\varphi(x,\kappa)}{d\,\kappa} = s_b\varphi(x)\ \Theta'(\varphi). \tag{2}$$

Performing integration on κ and then plugging its maximal value, we get the FFBRST transformation

$$\delta_b\varphi(x) = s_b\varphi(x)\ \Theta(\varphi). \tag{3}$$

The resulting FFBRST transformations having field-dependent parameter are symmetry of the Faddeev-Popov action but not nilpotent. However, the path integral measure of the generating functional changes non-trivially under FFBRST symmetry and consequently leads to a non-trivial local expression for the Jacobian. To evaluate the explicit form of the Jacobian corresponding to the functional measure, we define a (source free) generating functional for an arbitrary gauge theory consisting an effective action $S[\varphi]$ as follows,

$$Z[0] = \int D\varphi\, e^{iS[\varphi]}, \tag{4}$$

where $D\varphi$ refers to the full functional measure. Under the FFBRST transformation, the measure changes as [1]

$$D\varphi = J(\kappa)D\varphi(\kappa) = J(\kappa + d\kappa)D\varphi(\kappa + d\kappa) \tag{5}$$

This further reads,

$$\frac{d\ Log\ J(\varphi)}{d\,\kappa} = -\int d^4x \sum_\varphi \pm s_b\varphi(x)\frac{\delta\Theta'(\varphi)}{\delta\varphi}. \tag{6}$$

It is now straightforward to perform the integration over κ with an appropriate limit, which yields

$$Log\ J(\varphi) = -\int d^4x \sum_\varphi \pm s_b\varphi(x)\frac{\delta\Theta'(\varphi)}{\delta\varphi}. \tag{7}$$

This enable us to write the final expression for the Jacobian from above relation as follows:

$$J(\varphi) = Exp[-\int d^4x \sum_\varphi \pm s_b\varphi(x)\frac{\delta\Theta'(\varphi)}{\delta\varphi}]. \tag{8}$$

Here, we find that the expression for Jacobian can be estimated by the definite form of the parameter $\Theta'(\varphi)$. Therefore, one does not require an ansatz for local functional to be determined through further constraints. Hence, with this expression of the Jacobian we note that the FFBRST symmetry transforms the generating functional given in (4) as following:

$$\int D\varphi'\, e^{iS[\varphi']} = \int J[\varphi]D\varphi\, e^{iS[\varphi]} = \int D\varphi\, e^{i(S[\varphi]+Log\ J[\varphi])} = \int D\varphi\, e^{i(S[\varphi]-\int d^4x \sum_\varphi \pm s_b\varphi(x)\frac{\delta\Theta'(\varphi)}{\delta\varphi})}. \tag{9}$$

Here we stress that the final generating functional corresponds to the same theory but with a modified action (due to an extra piece). The specialty of present formulation is that we compute the Jacobian directly from the definite field-dependent parameter. This enables us to skip certain technical steps of procedure and produce exactly the same results. Finally, we remark that although the two specific models are discussed for illustration purpose, it is general enough to produce all the results obtained through original FFBRST transformation.

3. EXAMPLES

In the first example, we establish the connection between Lorentz gauge and axial gauge for YM (1-form gauge) theory using revised FFBRST transformation derived in section II which is the result of [21]. However, in second example, we justify the same for (Abelian) 2-form gauge field theory.

A. YM theory: Relating different gauges

The standard expression for the generating functional describing YM theory in Lorentz (covariant) gauge is given by

$$Z_L^{(1)} = \int D\varphi\, e^{iS_L^{(1)}[\varphi]}, \quad (10)$$

where φ stands for the gauge field A_μ^α, the auxiliary field B^α, the ghost field c^α and the antighost field $\bar{c}^\alpha$, collectively. The effective action $S_L^{(1)}$ in Lorentz gauge has the following expression:

$$S_L^{(1)} = \int d^4x\ [-\tfrac{1}{4}\ F^{\mu\nu\alpha}F_{\mu\nu}^\alpha + \tfrac{\lambda}{2}(B^\alpha)^2 - B^\alpha\partial.A^\alpha - \bar{c}^\alpha\partial^\mu D_\mu^{\alpha\beta}c^\beta], \quad (11)$$

where λ is a gauge parameter and $D_\mu^{\alpha\beta}$ is the standard covariant derivative. The nilpotent BRST transformations, under which this effective YM theory in covariant gauge remains invariant, are given by

$$\delta_b\, A_\mu^\alpha = D_\mu^{\alpha\beta}c^\beta\Lambda,\ \ \delta_b c^\alpha = -\tfrac{g}{2}f^{\alpha\beta\gamma}c^\beta c^\gamma\Lambda, \qquad \delta_b\bar{c}^\alpha = B^\alpha\Lambda, \quad \delta_b B^\alpha = 0, \quad (12)$$

where Λ is an anticommuting global parameter.
Following above procedure, we write the generating functional describing the YM theory in the axial (non-covariant) gauge,

$$Z_A^{(1)} = \int D\varphi\, e^{iS_A^{(1)}[\varphi]}, \quad (13)$$

where the effective action in axial gauge is written by,

$$S_A^{(1)} = \int d^4x\ [-\tfrac{1}{4}\ F^{\mu\nu\alpha}F_{\mu\nu}^\alpha + \tfrac{\lambda}{2}(B^\alpha)^2 - B^\alpha\eta.A^\alpha - \bar{c}^\alpha\eta^\mu D_\mu^{\alpha\beta}c^\beta], \quad (14)$$

where η^μ is a constant four vector.
Further, following the procedure outlined in section 2, we construct the FFBRST transformations corresponding to the BRST transformations (12) under which the effective actions for the YM theory remain invariant. These transformations are demonstrated as:

$$\delta_b\, A_\mu^\alpha = D_\mu^{\alpha\beta}c^\beta\Theta(\varphi),\ \ \delta_b c^\alpha = -\tfrac{g}{2}f^{\alpha\beta\gamma}c^\beta c^\gamma\Theta(\varphi), \quad \delta_b\bar{c}^\alpha = B^\alpha\Theta(\varphi),\ \ \delta_b B^\alpha = 0. \quad (15)$$

Here $\Theta(\varphi)$ corresponds to an arbitrary field-dependent BRST parameter. Here we have just replace the parameter Λ of (12) by $\Theta(\varphi)$. To show the connection between Lorentz and axial gauges we begin with the Lorentz gauge YM theory, described by the effective action given in Eq. (11) and apply the FFBRST symmetry transformation with following particular parameter:

$$\Theta(\varphi) = \int_0^1 d\kappa\,\Theta' = i\int_0^1 d\kappa \int d^4x\ \bar{c}^\alpha(\partial.A^\alpha - \eta.A^\alpha). \quad (16)$$

Now, exploiting formula (8), we compute the Jacobian for functional measure under FFBRST symmetry with particular parameter given in (16) as following:

$$J = Exp[\int d^4x\,(B^\alpha\partial.A^\alpha + \bar{c}^\alpha\partial^\mu D_\mu^{\alpha\beta}c^\beta - B^\alpha\eta.A^\alpha - \bar{c}^\alpha\eta^\mu D_\mu^{\alpha\beta}c^\beta)\,]. \quad (17)$$

With this Jacobian the effective action for YM theory modifies (within functional integral) as

$$S_L^{(1)}[\varphi'] = S_L^{(1)} + Log\,J = \int d^4x\ [-\tfrac{1}{4}\ F^{\mu\nu\alpha}F_{\mu\nu}^\alpha + \tfrac{\lambda}{2}(B^\alpha)^2 - B^\alpha\eta.A^\alpha - \bar{c}^\alpha\eta^\mu D_\mu^{\alpha\beta}c^\beta] = S_A^{(1)}, \quad (18)$$

where $S_A^{(1)}$ corresponds to the Faddeev-Popov action in axial gauge. Hence, we conclude that under a particular choice of transformation parameter the FFBRST symmetry maps the Lorentz and axial gauges within generating functional. Moreover, this is a very general result which is valid not only for this particular set of gauges but for any pair of gauges. We, therefore, have reproduced exactly the same result of Ref. [21] but in elegant manner.

B. 2-form gauge theory: Relating different gauges

We start by writing the generating functional describing the (Abelian) 2-form gauge field theory in a particular covariant (Lorentz) gauge as [23],

$$Z_L^{(2)} = \int D\varphi\, e^{iS_L^{(2)}[\varphi]}, \tag{19}$$

where φ refers following fields $(B_{\mu\nu}, \rho_\mu, \tilde{\rho}_\mu, \beta_\mu, \phi, \sigma, \tilde{\sigma}, \chi, \tilde{\chi})$ collectively. The explicit form of Faddeev-Popov action for this theory is given in terms of two arbitrary gauge parameters λ_1 and λ_2 by

$$S_L^{(2)} = \int d^4x\ [\tfrac{1}{12}\, F^{\mu\nu\rho}F_{\mu\nu\rho} - i\partial_\mu\tilde{\rho}_\nu(\partial^\mu\rho^\nu - \partial^\nu\rho^\mu) + \partial_\mu\tilde{\sigma}\partial^\mu\sigma$$
$$+\beta_\nu\big(\partial_\mu B^{\mu\nu} + \lambda_1\beta^\nu - \partial^\mu\phi\big) - i\tilde{\chi}\partial_\mu\rho^\mu - i\chi\big(\partial_\mu\tilde{\rho}^\mu - \lambda_2\tilde{\chi}\big)]. \tag{20}$$

The usual nilpotent BRST symmetry transformations of the theory are given by,

$$\delta_b B_{\mu\nu} = -(\partial_\mu\rho_\nu - \partial_\mu\rho_\nu)\,\Lambda,\ \ \delta_b\rho_\mu = -i\partial_\mu\sigma\,\Lambda,\quad \delta_b\sigma = 0,\ \ \delta_b\tilde{\rho}_\mu = \mathrm{i}\beta_\mu\,\Lambda,$$
$$\delta_b\,\beta_\mu = 0,\quad \delta_b\tilde{\sigma} = -\tilde{\chi}\,\Lambda\,,\quad \delta_b\tilde{\chi} = 0,\quad \delta_b\phi = -\chi\,\Lambda,\quad \delta_b\chi = 0. \tag{21}$$

Here Λ corresponds to an infinitesimal global parameter. However, the generating functional describing Abelian 2-from gauge field theory in axial (non-covariant) gauge is given by,

$$Z_A^{(2)} = \int D\varphi\, e^{iS_A^{(2)}[\varphi]}, \tag{22}$$

where the explicit form of the Faddeev-Popov action in axial gauge reads,

$$= \int d^4x\ [\frac{1}{12}\, F^{\mu\nu\rho}F_{\mu\nu\rho} - i\eta_\mu\tilde{\rho}_\nu(\partial^\mu\rho^\nu - \partial^\nu\rho^\mu) - \tilde{\sigma}\eta_\mu\partial^\mu\sigma$$
$$+\beta_\nu\big(\eta_\mu B^{\mu\nu} + \lambda_1\beta^\nu - \eta^\mu\phi\big) - i\tilde{\chi}\eta_\mu\rho^\mu - i\chi\big(\eta_\mu\tilde{\rho}^\mu - \lambda_2\tilde{\chi}\big)], \tag{23}$$

where η_μ is an arbitrary constant four vector. In order to connect the Lorentz and axial gauges within generating functional corresponding to this theory given in (19) and (22) respectively, we construct the following FFBRST transformations:

$$\delta_b B_{\mu\nu} = -(\partial_\mu\rho_\nu - \partial_\mu\rho_\nu)\Theta(\varphi),\ \ \delta_b\rho_\mu = -i\partial_\mu\sigma\,\Theta(\varphi),\quad \delta_b\sigma = 0,\ \ \delta_b\tilde{\rho}_\mu = \mathrm{i}\beta_\mu\Theta(\varphi),$$
$$\delta_b\,\beta_\mu = 0,\quad \delta_b\tilde{\sigma} = -\tilde{\chi}\,\Theta(\varphi)\,,\quad \delta_b\tilde{\chi} = 0,\quad \delta_b\phi = -\chi\,\Theta(\varphi),\quad \delta_b\chi = 0. \tag{24}$$

where $\Theta(\varphi)$ is an arbitrary anticommuting parameter which depends on the fields in global manner. We make a particular choice for field-dependent BRST parameter as

$$\Theta(\varphi) = \int_0^1 d\kappa\,\Theta' = -\int_0^1 d\kappa \int d^4x\ [\tilde{\rho}_\nu\big(\partial_\mu B^{\mu\nu} - \eta_\mu B^{\mu\nu} - \partial^\mu\phi - \eta^\mu\phi\big) + \eta^\mu\phi\big(\partial_\mu\rho^\mu - \eta_\mu\rho^\mu\big).$$

Now, we apply the FFBRST transformations given in (24) to the generating functional given in (19) and consequently calculate the expression for Jacobian utilizing the relation (8):

$$J = Exp[\int d^4x\,(-i\tilde{\rho}_\nu\partial_\mu(\partial^\mu\rho^\nu - \partial^\nu\rho^\mu) + i\,\tilde{\rho}_\nu\eta_\mu(\partial^\mu\rho^\nu - \partial^\nu\rho^\mu) + \tilde{\sigma}\partial_\mu\partial^\mu\sigma - \tilde{\sigma}\eta_\mu\partial^\mu\sigma$$
$$-\beta_\nu\big(\partial_\mu B^{\mu\nu} - \eta_\mu B^{\mu\nu}\big) + \phi\partial_\mu\beta^\mu - \phi\eta_\mu\beta^\mu + i\tilde{\chi}\partial_\mu\rho^\mu - i\tilde{\chi}\eta_\mu\rho^\mu + i\chi\big(\partial_\mu\tilde{\rho}^\mu - \eta_\mu\tilde{\rho}^\mu\big)].$$

Therefore, with this Jacobian expression the effective action in Lorentz gauge, $S_L^{(2)}$, changes (within functional integral) as following:

$$S_L^{(2)} + Log\,J = \int d^4x\ [\frac{1}{12}\, F^{\mu\nu\rho}F_{\mu\nu\rho} - i\eta_\mu\tilde{\rho}_\nu(\partial^\mu\rho^\nu - \partial^\nu\rho^\mu) - \tilde{\sigma}\eta_\mu\partial^\mu\sigma$$
$$+\beta_\nu\big(\eta_\mu B^{\mu\nu} + \lambda_1\beta^\nu - \eta^\mu\phi\big) - i\tilde{\chi}\eta_\mu\rho^\mu - i\chi\big(\eta_\mu\tilde{\rho}^\mu - \lambda_2\tilde{\chi}\big)] = S_A^{(2)}$$

Eventually, the FFBRST symmetry transformation with a particular transformation parameter (21) maps the Lorentz and axial gauges of (Abelian) rank-2 tensor field theory within generating functional as follows:

$$Z_L^{(2)} \xrightarrow{FFBRST\ Transformation} Z_A^{(2)},$$

which is exactly same result obtained in [23]. Therefore, we conclude that the revised FFBRST transformation developed in section II is more elegant than the original FFBRST transformation. We hope such analyses will be helpful in many more applications.

4. CONCLUSIONS

Gauge theories have found incredible applications in the modern physics. The standard quantization procedure of gauge theories involves the proper gauge fixing. However, being many choices of such gauge fixing, the most common gauge fixing conditions are the Lorentz and the axial gauges. Even though the gauge condition interrupts the gauge invariance, theory finds a fermionic rigid BRST invariance. The FFBRST transformations, which are the generalization of BRST symmetry, have found enormous applications in the various contexts. For instance, these connects the various gauges of the gauge theories, finds roots of Gribov ambiguity and play a vital role in Cho-Faddeev-Niemi decomposition etc.

We have developed a simplified way to find the Jacobian corresponding to the path integral measure under FFBRST symmetry transformations. The resulting Jacobian relies on the infinitesimal field-dependent transformation parameter explicitly. For any particular choice of parameter the Jacobian can be computed very easily which amounts an extra piece to the BRST exact part of the Faddeev-Popov action. Furthermore, we have shown that our formulation produces the same results as by the original FFBRST transformation. In this regards, we have established the connection between covariant and noncovariant gauges of (non-Abelian) 1-form and (Abelian) 2-form gauge theories which are the results of [21] and [23] respectively. The specialty of present formulation is that we compute the Jacobian directly from the field-dependent parameter of transformation. Therefore, we skip the certain technical steps of procedure and produce exactly the same results. Finally, we remark that although the two specific models are discussed for illustration purpose, it is general enough to produce all the results obtained through original FFBRST transformation.

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